ABRASIVES

PRODUCTS OF CANADA

TECHNOLOGY AND APPLICATION

Part IV

ARTIFICIAL ABRASIVES

AND MANUFACTURED ABRASIVE PRODUCTS AND THEIR USES

V. L. EARDLEY-WILMOT

MINES BRANCH
DEPARTMENT OF MINES
OTTAWA
1930

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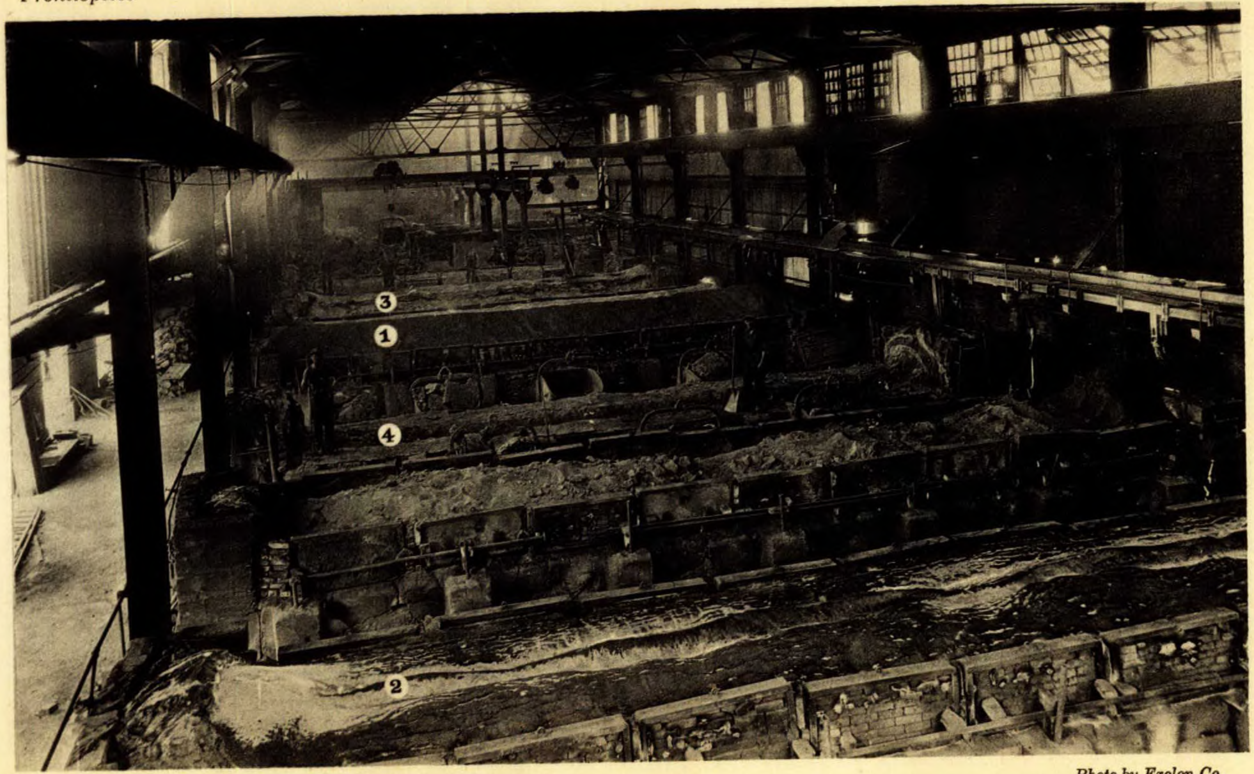

Photo by Exolon Co.

Silicon carbide furnaces in different stages of operation, showing also overhead dumping bucket system: 1, loaded, ready to burn; 2, burning; 3, loading; 4, unloading.

CANADA

DEPARTMENT OF MINES

HON. CHARLES STEWART, MINISTER; CHARLES CAMSELL, DEPUTY MINISTER

MINES BRANCH

JOHN McLEISH, DIRECTOR

ABRASIVES

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Part IV

Artificial Abrasives and Manufactured Abrasive Products and their Uses

BY

V. L. Eardley-Wilmot

OTTAWA
F. A. ACLAND
PRINTER TO THE KING'S MOST EXCELLENT MAJESTY
1929

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INTRODUCTORY

In recognition of the importance of the abrasive industry, and the many inquiries concerning the uses, sources of supply, preparation, and markets of the numerous minerals and materials included under the heading of Abrasives, the writer has made an investigation resulting in a series of bulletins embracing the subject in all its phases.

The following publications dealing with abrasives are issued as separate bulletins:—

Part I. Siliceous Abrasives: Sandstones, Quartz, Tripoli, Pumice, and Volcanic Dust.

Part II. Corundum and Diamond.

Part III. Garnet.

Part IV. Artificial Abrasives and Manufactured Abrasive Products and their Uses.

In the bulletin on Siliceous Abrasives will be found a general introductory and a table giving the varieties of natural abrasives, forms in which they are used and their principal uses, also a table showing the production of the various natural abrasives by countries between 1913 and 1923.

Up to the present there has been no information in Federal or Provincial reports concerning artificial abrasives and their manufactured products other than very brief references in statistical reports. During the years 1924-27 the writer visited all the principal artificial abrasive and grinding-wheel manufacturers in Canada and in the United States, as well as a large number of plants in which these abrasives are extensively used.

Special thanks are due to Mr. L. E. Saunders of the Norton Company for his co-operation and loan of the several cuts reproduced in this report; also to Mr. F. J. Tone of the Carborundum Company for information given during the writer's visits and by correspondence. Appreciation is also extended to the owners of the many plants visited, several of whom have kindly supplied some of the photographs included within; also to those others who have taken considerable time and trouble in replying to the many letters asking for information.

Special attention is drawn to the periodical "Abrasive Industry" through which and its Editor, Mr. F. B. Jacobs, the writer has obtained much information.

PART IV

ARTIFICIAL ABRASIVES

The term "artificial" abrasives is somewhat of a misnomer and to the uninitiated is likely to convey the wrong meaning. For this reason the term "manufactured" abrasives is now being gradually introduced, but as these abrasives are still universally known as artificial the term will be used throughout this report.

The recognized artificial abrasives are: silicon carbide, which was discovered in 1891, and is the hardest known material next to diamond; crystalline oxide of aluminium, known as fused alumina or aluminous abrasive, only very slightly softer than silicon carbide and was first commercially produced as an abrasive in 1900; and metallic abrasives in the form of steel shot and grit, also steel wool.

The main distinction between the two former is the greater brittleness of the silicon carbide. It is therefore mainly used on metals of low tensile strength and for most of the non-metals; whereas fused alumina is the standard abrasive for steels and all materials of high tensile strength.

These abrasives and their products are detailed separately in the following pages.

SILICON CARBIDE

Silicon carbide, a monocarbide of silicon (SiC) is, with the exception of diamond, the hardest known substance. It has a greater hardness than corundum, but is considerably more brittle.

OCCURRENCE

Although silicon carbide has not yet been found occurring naturally on this planet, several instances of its occurrence in meteorites are known. A notable example is that of the meteorite of the Canyon Diablo in Arizona, containing over 90 per cent iron in which considerable amounts of greenish coloured crystals have been identified as silicon carbide by Moissan, Kunz, and Huntington. These beautiful crystals of natural silicon carbide were first isolated by Moissan in 1904, and are known as *moissanite.*

There are two types of silicon carbide—crystalline and amorphous. When silica and carbon are heated in an electric furnace, the silica begins to combine with the carbon at 1460°C., forming greenish amorphous silicon carbide and oxycarbides of silicon, the mixture being the Siloxicon of commerce. The crystalline carbide is first formed at about 1840°C., but at 2200°C. it is decomposed into volatile silicon and solid amorphous graphitic carbon. The crystalline variety is a high-grade abrasive, but the amorphous carbide, which is used as a refractory material, has no abrasive qualities and will not be described in detail in this report. Unless otherwise stated the mention of "silicon carbide" or "carbide" refers to the crystalline variety.

PROPERTIES

Chemical Properties

Composition

Chemically pure silicon carbide consists of 70·29 per cent silicon and 29·71 per cent carbon. The industrial carbide usually contains a little iron, aluminium, calcium, and magnesium totalling less than 1 per cent. The industrial amorphous variety contains about 5 per cent iron and aluminium in addition to the above impurities.

Solubility

Silicon carbide is not affected by acids including hydrofluoric either alone or mixed with nitric acid. It is slightly attacked by chlorine gas at 600°C. and very rapidly at 1200°C., but is inert to sulphur vapours. Above 2000°C. an intimate mixture of powdered silica and silicon carbide is converted into silicon and silicon monoxide. A mixture of lime and magnesia slowly but only partially attacks it at 1000°C. Calcium and magnesium silicates also act in the same manner. At dark red heat it is attacked by fused soda or potash and basic fluxes. Sodium silicide attacks it at 1300°C. and destroys it rapidly in the presence of oxidizing gases.

Action of Heat

In an oxidizing atmosphere silicon carbide is converted into graphite at 2200°C. Up to 1350°C. there is barely any action other than a very superficial oxidization, but at 1500°C. this becomes more apparent resulting in a thin layer of transparent fused silica. This layer somewhat retards the action until at 1750°C. the silica becomes liquid and the oxidizing action becomes more rapid. In a reducing atmosphere there appears to be little or no effect on the carbide.

Compounds.

Silicon carbide combines with several monoxides of metals forming an alloy of silicon and the metal with the liberation of carbon monoxide; at 800°C. it combines with the oxide of copper, and between 1350° and 1370°C. with the monoxides of iron, nickel, manganese, chromium, and others. The carbon content of the alloys so produced is very low. A similar reaction will take place with the higher oxides when carbonaceous material is present.

Physical Properties

Crystallography

Commercial silicon carbide usually occurs as very slender crystals or needles with sharp outlines and very acute angles, caused by the breaking up of crystals of more regular form. The normal crystals have the appearance of hexagons which are sometimes quite thick and show parallel striations caused by the edges of flat crystals of gradually diminishing size, growing on top of one another. These often occur in the form of chisel edges in vugs of the mass. A sample of typical silicon carbide is shown in Plate II.

Colour, etc.

Silicon carbide crystals are colourless when made in the laboratory by the reaction of pure carbon and silicon. The industrial product passes from an emerald green to a dark grey-black or even jet black according to the proportion of iron and free carbon which they always contain as impurities, a very small quantity of either being sufficient to considerably darken the colour. The amorphous variety is a grey-green colour.

The *lustre* is brilliant and the crystals often reflect beautiful iridescent colours.

The *density* varies between 3·12 and 3·22; silicon carbide, therefore, is one of the lightest known high-grade abrasives. Its *apparent density* is about 1·85.

Its *hardness* is 9·5 to 9·75 in Moh's scale, being between diamond (10) and corundum (9), and is second in the scale of all known materials either natural or artificial. It will cut rubies and sapphires and will produce long deep cuts in the hardest alloy steel.[1] It has a low degree of *toughness* as it is extremely brittle. It is this combination of hardness and weakness that makes it such a valuable abrasive for certain classes of work.

The *heat conductivity* of the crude carbide is high, approximately 0·015 gram-calories per second at 1,000°C. which is about the same as graphite. The carbide rapidly comes into equilibrium with the surrounding temperature and is capable of resisting sudden and extreme changes of temperature without cracking or breaking. It is a good *electrical conductor*, its conductivity rapidly increasing with the rise in temperature, its *electrical resistivity* being 50 megohms per cubic centimetre at 25°C., 14·5 at 600°C., and 0·65 at 1,400°C. It has found commercial application because of these properties.

Silicon carbide has no *melting point*, but is suddenly decomposed into its two constituents at a high temperature, 2,200°C.

The *coefficient of linear expansion* decreases as the temperature increases and varies from $6\cdot58 \times 10^{-6}$ at 100°C. to $2\cdot98 \times 10^{-6}$ at 900°C.

The *specific heat* is 0·140 at 0°C., 0·261 at 300°C., 0·275 at 600°C., and 0·285 at 900°C.

The *index of refraction* is approximately 2·74.

HISTORICAL

Discovery and Early Experiments

The credit for the discovery of crystalline silicon carbide is assigned to Dr. E. G. Acheson, although its presence had been observed ten years previously. In the spring of 1891, when conducting research on the manufacture of diamonds and hard abrasives at Monongahela, western Pennsylvania, Acheson observed a few minute crystals of brilliant lustre adhering to the carbons of his small electric furnace. A few simple tests proved that they were not synthetic diamonds, but a material second only to diamond in hardness. The furnace in which this was made consisted simply of an iron pot lined with retort carbon, thus forming a crucible, the electrode being a cylinder of retort carbon which could be raised or lowered when suspended within the pot so that the electric arc could be adjusted. The mixture used was clay and carbon.

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[1] Except the tungsten carbide alloy.

In order to obtain more of these crystals Acheson designed a larger and better furnace of rectangular design having adjustable carbons placed at either end. An alternating electric current was used which had an intensity of 100 to 200 amperes and an electromotive force of 50 volts.

Since the raw materials used were mainly silicate of alumina (clay) and carbon, Acheson believed the new compound to contain carbon and alumina, so he named it "carborundum" a word derived from "carbon" and "corundum" (the natural crystallized alumina). Although the compound is still universally known by that name the nomenclature is incorrect as Acheson had the new product analysed and discovered its true composition and thus recognized the important part silicon plays in its formation. He, therefore, made new experiments using silica in the place of clay and modified the principle of his furnace, using a resistance instead of an arc type, by replacing the movable electrodes for a single cylinder of retort carbon, and later a core of graphite, which passed through the mixture and carried the electric current.

In his patent (U.S. Pat. 492767, Feb. 28, 1893, filed in May 1892) Acheson describes this method and mentions the addition of salt as a flux and a means of facilitating the current by a core of graphite between the electrodes. A sketch of the furnace described in the above patent is shown in Figure 1.

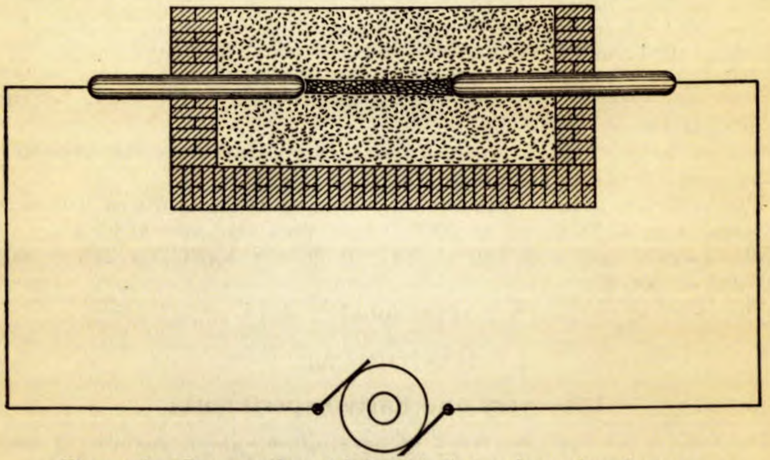

Figure 1. Cross-section of Acheson's first carborundum furnace.

The results obtained by this type of furnace and mixture were so much better than that obtained previously that, with only comparatively slight alterations in details, the same procedure is used for the commercial manufacture of silicon carbide to-day.

Previous to Acheson's experiments, Marsden in 1880 mentioned the presence of pale yellow crystals when studying the solubility of silica found in fused silver for which he used a carbon-lined crucible. Two years later, May 16, 1882[1], A. Colson read a paper on the formation of a new compound of silicon and carbon with the formula SiC_2, before the Academie

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[1] Comptes Rendus, vol. CIV, p. 1316 (1882).

des Sciences. In the same year as Acheson's discovery, Moissan when repeating Marsden's experiments proved these yellow crystals to be silicon carbide. At about the same time Moissan also obtained a coating of fine needles of silicon carbide crystals from the direct union of carbon and silicon vapours. In several other experiments, Moissan proved the existence of small quantities of this carbide. Although Marsden's and even Moissan's discoveries may have been slightly previous to that of the American scientist, they did not publish their work until after the publication of Acheson's experiments, but in any case the commercial production of crystalline silicon carbide is entirely due to the work of the latter.

In 1892 amorphous silicon carbide was produced in France by Schutzenberger[1] by heating a mixture of crystallized silicon and silica in a triple crucible, the intervening spaces being packed with lampblack, while the inner crucible was made of retort carbon. The amorphous silicon carbide was formed by the reducing action of silicon on carbon monoxide at a very high temperature.

Commercial History

In 1891, E. G. Acheson, having collected enough crystals from his first experiment to fill a small vial, induced some New York jewellers to try out the powdered material as a substitute for diamond dust for polishing precious stones. The results were so successful that he obtained his first order, the price being 40 cents per carat or $880 per pound. The Carborundum Company was chartered September 28, 1891, and commenced business in Monongahela, Pennsylvania, the following month.[2] Improved methods of manufacture increased the output enabling the price to be cut in half and broadening the market for the daily output of 4 ounces. This carborundum was found to be so superior to emery for valve grinding that it became greatly in demand at $10 per pound. The jewellers naturally ceased to buy at the higher price since they soon found that they could get just as good results by further grinding down the material used for valve grinding. This new use quickly exhausted the stock of carborundum and enlargements to the plant were necessary, resulting in the manufacture of 920 pounds during the first 15 months, but only 54 pounds were sold. In the following year the company produced 45 tons of carborundum, but only sold about half the output. In 1893 the company started making small wheels and points for dental work, which were highly successful, and, later, small vitrified wheels for general grinding purposes.

With very little but unbounded faith to justify such a step, the company in 1895 began the erection of the Niagara Falls plant and was one of the first firms to enter into a contract with the Niagara Falls Power Company (which was then nearing the completion of its first tunnel) for 1,000 electrical h.p. which would allow them to produce 900 tons of carborundum per year. This plant was completed in 1896 and consisted of the furnace department; crushing and grading plant and a wheel-making department. At that time emery was the principal hard abrasive and was considerably cheaper. Those engaged in routine work were slow to adopt an entirely new material, the claims for which passed their belief. However, the great superiority of carborundum over emery was proved and eventually

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[1] Comptes Rendus, vol. CXIV, p. 1089 (1892).

[2] Pamphlet issued by the Carborundum Company.

outweighed the difference in price, so that in 1898 the production of the first 1,000 h.p. was absorbed and another 1,000 h.p. was contracted for and put into use. The Carborundum Company then established a small subsidiary plant in Canada at Niagara Falls, Ontario, mainly, at first, in order to maintain the validity of the Canadian patents.

The original patents have now long since expired and silicon carbide, under several trade names, is being made on the American continent by four companies having six plants (three of which are in Canada) with a total annual output of twenty-five thousand tons. The price, which was originally $880 per pound in 1891, is now about 12 cents.

Foreign History

In October 1893, two French engineers, L. Peresse and Baron R. de Batz, introduced this abrasive into France and the following year a factory was built at La Bathie near Albertville in Savoie. In 1900, silicon carbide was manufactured by the Compagnie Internationale du Carborundum at Dresden, Germany, and at Alt Benetek, Austria.

In Europe, at present, silicon carbide is manufactured in five plants, one each being in Germany, France, Norway, Sweden, and Czechoslovakia.

MANUFACTURE OF SILICON CARBIDE

Canadian and American Methods

A brief outline of the manufacture of silicon carbide is as follows:—

The principal ingredients are crushed coke and silica sand which are mixed with small proportions of sawdust and common salt. The mixture is loaded into a rectangular electric furnace and subjected to intense heat for 36 hours. After cooling, the sides of the furnace are taken down and the outer crust of the fused mass removed revealing a mass of the silicon carbide crystals loosely knitted together. The crystals are broken up, pulverized, cleaned by water and chemicals, and finally graded into the various sizes of grain required by the trade. Since the basic patents covering the above methods of manufacture have expired, the silicon carbide produced by the various companies is exactly the same except for minor details. A more detailed description and theory of action during operations are given below.

The Furnace

The electric furnace consists of a U-shaped trough of firebrick supported on brick piers in such a manner that the furnace bottom is kept cool by air circulation. The sides are made of movable sections of firebrick the top being left open to the air. The sizes of the furnaces vary in the different plants and range from 6 to 10 feet wide and 6 feet high by 25 to 50 feet long. At either end of the trough is a reinforced pier through which large water-cooled, carbon rod electrodes are run and to which the electric current is brought through heavy cables. The construction of the furnace is shown in Plate V. There has been little alteration from the original type of furnace of 30 years ago other than slight modifications such as improvement in the water-cooling system, substitution of movable sides for solid brick walls, and changes in the number of electrodes.

The Charge and Functions of the Various Ingredients

The *coke* used is usually high-grade petroleum coke having a minimum quantity of ash. Bituminous coke is occasionally used, but the carbide produced is not so pure and is utilized as a cheaper abrasive in silicate or rubber bond wheels. The crude coke is dried, crushed to a dust, and kept in storage bins.

The *sand* is a pure fine quartz sand free from iron and is obtained mainly from Illinois, though pure material comes from other sources. Some of the Canadian plants use material from the sandstone quarry at St. Canute, Quebec.

The *sawdust* should be coarse and granular and preferably obtained from hard woods. Its main function is to make the mass porous and allow the accumulating gases to gently escape. It is this high porosity and skeleton-like structure of the finished carbide that makes it so easy to break up. Without the sawdust the mass would be formed into a solid lump, devoid of individual sharp crystals. Moreover, if no vents for the escaping gases were present the danger of the whole mass exploding would be very great.

The *salt* in the powdered form comes from the nearest source of supply, principally the Windsor district of southern Ontario. The salt reacts with any iron or oxides present, forming volatile chlorides which escape into the air. Although the addition of common salt is the usual practice, it is not necessary if the purest ingredients are used with the highest grade petroleum coke.

All the above ingredients are kept separate in large storage bins and from these mechanically conveyed to bins over the weighing machines, from which they are dumped out in their proper proportions and conveyed to rotary mixers. The approximate proportions in per cent by weight are as follows: sand, 53; coke, 28; salt, 1½; and sawdust, 7½. These proportions, however, vary slightly according to the ideas of the manufacturer and are governed by the temperature conditions, purity of ingredients, and the type of silicon carbide to be produced. The mixed charge then goes to the furnace room by an overhead system.

The Laying of the Charge

By means of dumping buckets controlled by an overhead system (*see* Plate I) a portion of the charge is distributed along the floor of the furnace trough up to the level of the electrodes, a narrow trench being dug along the centre of the entire length. This trench is then filled with a core containing a mixture of graphite (converted in a former run) and fresh granulated coke, thus making a direct connexion between the electrodes along which the current flows. A layer of very fine coke or graphite is placed close to the electrodes, while the electrode ends which penetrate into the mixture are protected with thin, easily removable iron plates. It is the high resistance to the passage of the current, due to the fresh coke, that causes the intense heat required for the operation. The physical condition of this central core is consequently of considerable importance. It is usually built in the shape of a rectangle 2 to 3 feet wide and 12 to 18 inches deep. The action of the heat on this core is described later. The remainder of the charge is then dumped along the top of the furnace and packed by hand around and above the core, forming a mound down the centre. A loaded furnace ready to burn is shown in Plate V. A more uniform product is obtained by adding a higher proportion of silica to the mix below the core, since, during the operation of the furnace, the ratio of the silica to the carbon increases in the upper part of the charge. This feature is patented by Otis Hutchins (U.S. Pat. 1331435, Feb. 17, 1920, for Carborundum Company). The total weight of a charge for a modern furnace is about 35 tons including the core.

The furnaces are usually run in groups of four which are utilized in a cycle as follows: loading, running, cooling, and unloading. Some operators run the furnaces in groups of six, there being in addition a spare furnace and an empty ready to load. On the American continent each plant has four to five units so that one furnace per unit is producing continuously. These are shown in Plate I.

The Current and its Action

The electric current is stepped down in stages from the primary current and is regulated by means of a rheostat that allows it to be operated between 100 and 350 volts. The power consumption for each furnace appears to vary somewhat with the different manufacturers. The starting voltage is usually about 300 volts and decreases to a steady run of approximately 200 volts. The large furnaces each operate at 6,000 to 7,500 amperes and 1,500 k.w. with a total of 40,000 to 50,000 k.w. hours for an average run of 36 hours.

After about 4 hours of operation the maximum temperature of approximately 4,200°F. (2,200°C.) is reached and the current remains constant at 115 to 125 volts and 6,000 amperes. At this stage the sawdust has burnt out and small blue flames of burning carbon monoxide appear at all the joints in the furnace as well as on the top of the mixture. This is produced by the reaction of the silica and part of the carbon as follows:

$$SiO_2 + 2C = Si + 2\,CO.$$

This reaction is immediately followed by the formation of silicon carbide. The silicon combines with the excess of carbon and the carbide is produced from the centre of the mass outwards. ($Si + C = SiC$.)

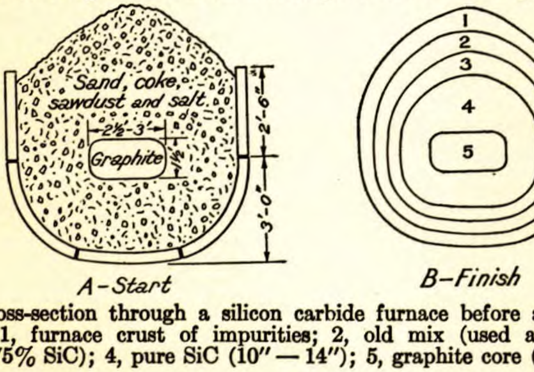
The carbon monoxide is not collected as a by-product because the action of the burning gas on the outside of the charge plays an important part in decreasing the temperature gradient and effectively prevents the outward flow of internal heat and incidentally conserves some of the electrical energy.

After 5 or 6 hours the mixture shrinks and cracks, when sheets of flame appear, coloured yellow by the salt. These are also accompanied by white fumes due to silicon vapour and fine coke ashes. At this stage more mixture is often thrown on top of the charge to maintain the load and to conserve heat. After 36 hours, the current is switched off and the electric cables transferred to the next furnace (which has been loaded) and put into operation.

The Furnace Products

The furnace is allowed to cool for 36 to 48 hours after which the sides are removed in sections. The mass consists of several concentric rings or layers of different products. The outside shell, known as "furnace crust", more or less fused together with salt and impurities, is thrown out. Next comes the "old mix" which is a mixture of unconverted charge and some fused material that has not otherwise been acted upon. This is removed and mixed in with the next charge and is, therefore, used up, except portions that are too badly caked with impurities and are discarded. The following layer of "fire sand", 2 to 4 inches thick, consists of 70 to 75 per cent of a grey-green amorphous silicon carbide (which is formed between 1,550° and 1,820°C.), and a small proportion of oxycarbides of silicon known as "Siloxicon". For many years this "fire sand" was thought to be of no commercial value, but since the discovery that it possesses high refractory properties, it is now separated and forms a valuable by-product for the manufacture of refractories. There is a sudden and clean line between the above amorphous material and the underlying porous mass of silicon carbide crystals loosely knitted together. The outer portion of this mass consists of beautiful needle-shaped, highly iridescent crystals often tinted a pale green to a deep blue-black. Closer to the interior the colour changes to a grey-black and the crystals somewhat lose their slender form and sharpness. This ring of silicon carbide is 10 to 14 inches thick and contains approximately 80 per cent silicon carbide, 10 per cent carbon, and 10 per cent unconverted silica. The quantity of this product is 4 to 6 tons depending on the capacity of the furnace. Finally there is the, central core, which has been entirely converted into amorphous graphite. The outer part of this core is a pseudomorph of the crystalline carbide, that is, although amorphous it assumes the crystalline outline of the silicon carbide and is known as "graphite skeletons". If the temperature and operation have been carefully controlled, the volume of the original core will remain constant and there will be a sharp line of demarcation between the graphite core and the surrounding crystalline silicon carbide. The temperature of the formation of silicon carbide is between 1,820° and 2,200°C, above which it is converted into graphite, so that the latter temperature must be confined to the core itself, otherwise the valuable carbide will be graphitized.

A section through the finished charge is shown in Figure 2.



A-Start B-Finish

Figure 2. Cross-section through a silicon carbide furnace before and after action is complete: 1, furnace crust of impurities; 2, old mix (used again); 3, fire sand (2" — 4" 75% SiC); 4, pure SiC (10" — 14"); 5, graphite core (unchanged).

Special Silicon Carbide

Very few processes are known by which the abrasive temper of silicon carbide can be varied. It thus differs in this respect from fused alumina in which the number of combinations that produce variations in temper is very large. There is a slight difference of abrasive qualities of the carbide made from the purest materials, such as the almost transparent green product used to some extent for dental work. Recently a jet black silicon carbide has been put on the market for use in the coated abrasive trade. However, no practical difference exists between its abrasive qualities and that of the ordinary, but it is preferred by some users because of its pleasing colour when applied to papers or cloths.

A few patents for the manufacture of different types of silicon carbide were taken out about 20 years ago by F. J. Tone for the Carborundum Company. One of these which is a retreatment process consists of embedding the regular porous carbide in a mass of silica and carbon and then heating the charge to the temperature of the formation of silicon carbide in the ordinary furnace. The vapours of silicon and carbon build upon and within the mass of carbide crystals and convert them into a dense compact and non-porous state. It is believed that the silicon has the property of reducing the carbon monoxide at certain high temperatures just below the decomposition point of silicon carbide and that the carbide thus formed is deposited in the pores of the crystalline mass making it dense and compact (U.S. Pat. 913324, Feb. 23, 1909, F. J. Tone, Carborundum Co.).

A somewhat similar material to the above was at one time made at La Bathie, France. The process consisted of re-treating the impure amorphous silicon carbide or fire sand obtained as the by-product of the main reaction. This was heated in the electric furnace for 16 to 18 hours at a temperature higher than that of its formation and under these conditions the Siloxicon (oxycarbide of silicon) which is always present, is reduced and the salt and other impurities are volatilized. The material then becomes purified and crystallized and, although porous, is denser than the ordinary carbide.

A compact silicon carbide was also made in Germany, but by an entirely different process. The final shapes required—whether wheels, bricks, blocks, etc.—were moulded or cut from graphite or very pure carbon and were then subjected to the action of silicon vapour at a very high temperature in order to impregnate them with the silicon. The direct union of the silicon and the carbon thus effected within the walls of the presses, transforms the carbon shapes into massive silicon carbide. It was found, however, that the material disintegrated under pressure, consequently it is not used to any extent as an abrasive, but more for electrolytic cells and as a material for condensing acid vapours.

Silicon carbide grain or powder is mixed with a temporary binder, such as glue, moulded into the required shape and treated in an electrical furnace at the temperature originally used to make the carbide. The carbide recrystallizes into a hard dense mass occupying the same volume as before treatment. The forms are used for refractory bricks, crucibles, abrasive blocks, etc. (U.S. Pat. 650234, May, 1900, F. A. J. Fitzgerald)

PREPARATION AND GRADING OF SILICON CARBIDE

Preparation

The crude lump silicon carbide is crushed in a pan mill, about 7 feet diameter, having two large mullers of about 3 tons each equipped with chilled iron tires. These mullers rotate as the pan turns under them, the lumps being carried to them by means of baffles (Plate VIA). About 800 pounds of the grain is disintegrated in about one hour and constitutes a charge which is then shovelled onto a belt conveyer passing to storage bins. From the bins the crushed material passes over an 8 by 10-mesh vibrating screen, the oversize being crushed in a ball mill and returned, while the undersize goes to lead-lined chemical tanks with plugs at the bottoms.

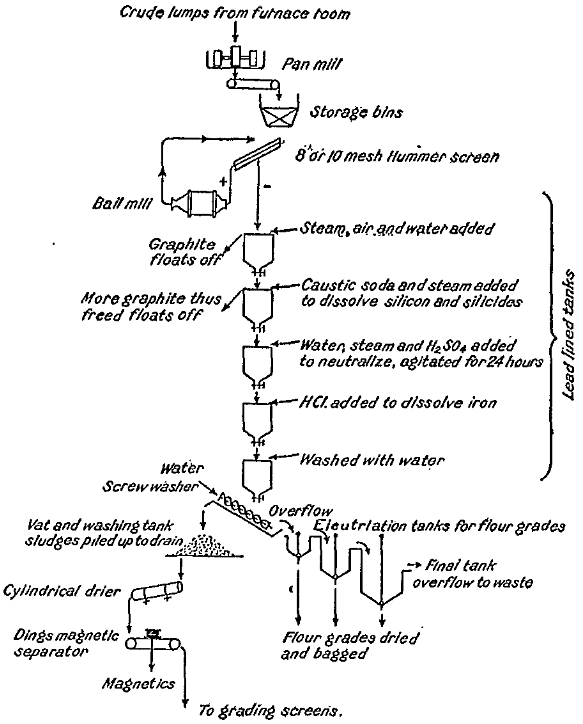


Figure 3. Flow-sheet of a composite silicon carbide cleaning and preparation plant.

In the first tank the abrasive is washed with steam and water when most of the graphite floats off over the top. Caustic soda is then added to dissolve the silicon and silicides present, and during the process the entrapped graphite, which occurs between the laminations of the silicon carbide, is liberated and also floats off. The sludge after settling is run out into another tank, washed with steam and water, neutralized with sulphuric acid, and agitated for 24 hours. Hydrochloric acid is then added to dissolve the iron, after which the residue is well washed until all the iron is removed as determined by testing with potassium ferrocyanide.

One method of washing is to convey the sludge up an inclined trough against a down-flowing stream of water, the fine particles which are carried away by the water go to the settling-tanks. The washed sludge is piled up to drain and then dried in cylindrical driers. While still warm the carbide is sent over a magnetic separator to remove any iron mechanically introduced (particularly during the early crushing process), after which the material passes into the grading department and is graded into the numerous sizes required by the trade. The overflow from the various tanks and final washings is conveyed by launders into a series of settling-tanks or classifiers of gradually increasing volume.

The mud from the bottoms of each of these tanks is dried separately and graded into multiples of F— or "flour", and used for such purposes as valve and glass grinding. The final overflows are allowed to settle for definite periods of time, usually 28, 32, 40, 50, and 60 minutes and are known as "32-minute" or "60-minute" or as 320, 500, 600, etc., powders (Carborundum Company symbols), the size of which are controlled by the microscope. Figure 3 shows a flow-sheet of a composite silicon carbide cleaning and preparation plant. A photomicrograph of silicon carbide grain is shown in Plate XIXC.

The Grading of the Abrasives

The "grading" of an abrasive refers to the separation of the grain into numerous sizes or "grades", the symbol number being the mesh that the individual grain will just pass through. There are 21 to 24 grades of the following sizes: 6, 8, 10, 12, 14, 16, 20, 24, 30, 36, 40, 50, 60, 70, 80, 90, 100, 120, 150, 180, 220; also the powders F, FF, FFF, and 280 to 600.

The thoroughly dried product is first sent over "splitters". These are screens which divide the material into two or four groups of mixed sizes, a single 50 mesh or two of 20 and 70 mesh splitters may be used. Each group is then graded to correspond with the above series. The machines are usually inclined, rapidly vibrating (about 300 reciprocations per minute) troughs 24 to 30 feet long, 18 inches wide, and divided into 8 to 10 movable sections of 3 feet, over each of which the correct sized wire cloth or silk mesh is stretched (Plate VIB). The throughs and oversize from the splitters are fed direct to the head of each of the grading troughs, which are usually in pairs, the finest screen of the series being at the top. Either a small bin is attached to the base of each screen or a side opening provided from which the products are caught in paper-lined barrels. A coarse screen at the end of the trough catches and discards wood and other materials that might be accidentally introduced and the oversize abrasive is recrushed and sent back over the system. When the coarse meshes are in excess or when a greater proportion of the finer sizes is required, the coarse products are recrushed by steps in small rolls, care being taken not to overcrush and thus produce too many unsaleable fines.

On all except the larger sizes, silk bolting cloth is used because the openings are more uniform and do not clog so rapidly, but owing to recent improvements in the manufacture of fine wire cloth, these may be now more extensively employed. The products from each screen are continually examined and checked by small hand sieves and if oversize is noted the screens are at once changed by inserting spare frames that are always prepared in readiness. The arrangement of the grading department varies in different plants. For example, the grading may be done by allowing the grain to descend through or over screens having solid bottoms, which are arranged in a zigzag manner one below the other and tilted laterally. The throughs from each are caught on the trays and piped by gravity to the barrels while the oversize is lead to the top of the coarser screen below and so on down to the coarsest mesh.

Barrelling may be done on the same floor as the screening, or the various grades led down by pipes to the floor below. During filling, the opening at the barrel top should be as small as possible, and when filled, immediately closed and sealed with the paper in order to prevent contamination from dust or oil-impregnated atmosphere.

Proving

For certain trades requiring the highest accuracy in grading, such as for the use of abrasive papers or for precision grinding wheels, the −60 grades produced by the above methods have to be checked or re-sifted over silk screens, known as "proving silk". These have a larger sifting area, but a smaller capacity than the long screens. Before this operation the material is usually put over a magnetic machine in order to ensure that it is absolutely free from magnetic impurities.

The above described system of grading is applicable to all types of abrasives, either the natural corundum, garnet, emery, and quartz or the artificial silicon carbide and fused alumina. The former, particularly garnet, on account of the large average size of the concentrates require more intermediate crushing during the grading stages. The number of standard grades is also variable, the aluminous, with 24, being the greatest, exclusive of flour grades.

ANALYSIS OF SILICON CARBIDE

Purification of Commercial Silicon Carbide

For laboratory investigations or for certain analyses, it is necessary to purify the commercial carbide. The method described by Baraduc-Müller[1] is as follows:—

> The iron, alumina, magnesia and lime are eliminated by treating the crystallized carborundum with hot concentrated hydrochloric acid. It is then washed in boiling water with constant stirring. It is next agitated with a hot, dilute solution of caustic soda and washed again with boiling water and filtered. The powder obtained is dried and calcine according to the quantity either in a muffle furnace at a temperature of about 1,000° and frequently stirred so as to renew the surface of the powder in contact with the air, or in a combustion tube at about 500° in the presence of air or oxygen.
>
> This combustion destroys all the free carbon, leaving only its ash which still contains a little silica, alumina, oxide of iron, magnesia, and lime. These are eliminated by a second treatment with hydrochloric acid followed by washing and digestion in pure hydrofluoric acid.
>
> By washing thoroughly and for a long time with hot distilled water crystallized carborundum is finally obtained as pure as possible, and clear of all free elements such as iron, alumina, calcium and magnesium, or their salts, with the exception of those that are combined with silicon. These compounds of silicon exist in the state of solid solution or complex compounds within the molecule of carborundum and cannot always be freed from it.

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[1] Baraduc-Müller, L.: "Carborundum", Revue de Métallurgie (Feb. 1909).

Analysis

The impurities contained in the soluble parts from the first and second treatment in the process described above can be estimated by the ordinary methods and the free carbon obtained by the calcination also collected and estimated.

The silicon in the pure silicon carbide is estimated as silica by treatment with a mixture of carbonates and peroxide or nitrate of sodium. The carbonic acid is estimated by means of chromic acid mixed with bismuth sesquioxide in a combustion tube through which a current of oxygen is passed. This latter process is repeated in order to ensure the complete oxidation of the contained carbon.

FUSED ALUMINA

PROPERTIES

Physical Properties

The following properties refer to the various commercial aluminous abrasives and do not include the transparent and gem varieties.

Crystallography

Individual fused alumina crystals in small quantities are formed in the process of manufacture, although masses of long, sharp-pointed hair crystals occur often in the vugs. When magnified they are seen to be covered with parallel triangular barbs, due to the formation of gradually diminishing (towards the point), overlapping pyramids (Plate IV). In other instances groups of thin hexagonal crystals overlap triangular plates and lie in echelon formation within the vugs. Natural corundum crystallizes in the hexagonal system, either prismatic or tabular.

Colour, etc.

When pure the fused alumina abrasive is white and opaque. The ordinary commercial grades of the "regular" abrasive are varying shades of dark to reddish brown.

Massive crystalline alumina has a somewhat vitreous or pearly *lustre,* which diminishes in intensity in the smaller crystalline varieties.

The *density* varies between 3·93 to 4·01 according to the nature of the impurities present. Its apparent density is about 2·32.

The *hardness and toughness* vary according to the type of the abrasive. The hardness may vary from 9·2 to 9·6 in Moh's scale, but fused alumina is not quite so hard as silicon carbide. The toughness is considerably greater than the latter abrasive and the degree largely depends on the impurities present, the pure material being weaker than one containing 3 to 4 per cent iron and titanium, the toughest contains 2 per cent iron oxide and 2 per cent titanium oxide.

The *thermal conductivity* of the crude alumina is comparatively low, being about 0·0016 gram-calories at 47°C., but increases with a rise in temperature to about 0·0083 at 1,200°C. It is not so good an *electrical conductor* as silicon carbide, the resistivity (megohms per cubic centimetre) being about 120 at 528°C. but rapidly drops as the temperature rises.

The *coefficient of linear expansion* is considerably greater than that of silicon carbide at higher temperatures, being approximately $7 \cdot 5 \times 10^{-6}$ up to 900°C.

The *specific heat* appears to be approximately that of silicon carbide and varies from 0·183 at ordinary temperature to 0·279 at its melting point.

The *index of refraction* is high but less than that of silicon carbide and is about 1·76.

The *double refraction* of alumina is almost negative being about the same as quartz (0·008).

Modulus of elasticity is 52,000 kilograms per square millimetre and is therefore very high, being 2·5 times that of steel and exceeded only by that of iridium (52,500).

Pleochroism in ordinary light is strongly marked. This property serves to distinguish the fine-grained alumina from garnet and other non-pleochroic minerals.

Chemical Properties

Composition

The composition of the commercial abrasive varies according to the method of manufacture, the pure white material being over 99 per cent oxide of aluminium, while others may contain 94 or 95 per cent alumina with oxides of silicon, iron, titanium, and of numerous other metals which are often purposely included. These are mentioned later in dealing with the different processes of manufacture.

Solubility

The alumina is soluble in fused alkalis particularly potassium hydro- or pyro-sulphates. Although insoluble in most acids, it is very slowly attacked by boiling sulphuric. When treated with some chlorides and fluorides a reaction takes place. It is attacked by fluorine gas but not by chlorine; neither is it affected by hydrogen.

Fused alumina resists basic fluxes (for this reason it is used for lining lime and cement kilns), but is attacked by fused silica and siliceous fluxes. There is no effect on the alumina when exposed to an oxidizing atmosphere, but at a temperature of about 1,800°C. it combines appreciably with amorphous carbon with the slow formation of aluminium carbide. It does not appear to be affected by molten metals.

The *melting point* of fused alumina begins at 1,950°C., and at 2,050°C. the material is in a fluid state.

HISTORICAL

Artificial corundum, in the form of synthetic gems, has been known since 1837 when M. A. Gaudin made rubies by fusing a mixture of alum and potassium sulphate in a carbon crucible at a very high temperature, the desired colour being imparted by the addition of a little chromium.[1] Some years later J. J. Ebelmen produced white sapphire and coloured spinel by fusing the alumina at a high temperature with borax. In 1877 crystallized alumina of a size suitable for cutting into small stones was made by E. Frémy and C. Feil. Their process consisted of fusing lead oxide, alumina, and lead aluminate in a fireclay crucible. The silica of the crucible gradually decomposes the lead aluminate forming lead silicate which remains in the liquid state while the alumina crystallizes out as white sapphire. Rubies were formed by the addition of a little chromium.[2] During this period many other scientists devoted much work to the art of producing artificial corundum.

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[1] Gaudin, M. A. Compt. Rend., vol. 4, p. 999 (1837).

[2] For the history and manufacture of synthetic gems see Mellor, J. W.: "A Comprehensive Treatise on Inorganic and Theoretical Chemistry"; vol. V, pp. 259-260 (1924).

Although these early experiments proved conclusively that it was possible to produce artificial corundum, its use as an abrasive appears to have been never seriously considered until 1893 when Ivan Werlein of France took out a patent (French Pat. 233996, Nov. 11, 1893). The first commercial process, whereby a small production was made, appears to have been the outcome of the discovery of F. Hasslacher, Germany (German Pat. 85021, Nov. 28, 1894), who in 1894 used emery as the source of the aluminium oxide. In the following year (July 6, 1895) Werlein brought out a revision of his previous patent in which he introduced calcined bauxite in the place of emery. This appears to be the first record of the use of bauxite which is now universally employed in the process for the manufacture of the regular fused alumina abrasive. Three years later another German scientist, Dr. G. Döllner, produced fused alumina of exceptional hardness by the ignition of a mixture of powdered alumina and metallic oxides.

Previous to the year 1900 all the aluminous abrasives lacked "abrasive temper" but in May of that year Charles F. Jacobs, an American, filed a process patent (U.S. Pat. 659926, Oct. 16, 1900) for the manufacture of fused alumina from bauxite and for tempering the alumina to a degree of hardness suitable for abrasive purposes. The degree of this temper was controlled by means of his furnace in which the hearth could be gradually raised or lowered, thereby governing the rate of cooling and consequently the nature of crystallization (Figure 4).

Jacobs' process was the first commercially successful one for the manufacture of aluminous abrasives and is the one upon which the present production of the American abrasive is based. His original experiments previous to the issue of his patent appear to have been carried out in the plant of the Ampère Electrochemical Company about the time it moved from New Jersey to Niagara Falls, N.Y., in 1898. The material was produced in a revolving furnace of the Horry carbide type.[1] Jacobs' patents were taken over from this concern by the Norton Emery Wheel Co., Worcester, Mass. The first commercial production of fused alumina was made in the Norton plant erected at Niagara Falls, N.Y., in 1901, the crude abrasive being sent to Worcester for cleaning and grading. To this company, using Jacobs' patents, is largely due the present perfection of fused alumina, the production of which now far exceeds that of any other type of abrasive.

One of the early difficulties encountered was the mechanical removal of the metallic impurities which remained suspended throughout the fused mass. Shortly after commercial operations were commenced, Charles H. Hall in his experiments in the purifying of bauxite for the manufacture of aluminium found that by the addition of iron to the charge the impurities were rendered sufficiently magnetic to be easily removed (U.S. Pat. 677207-9, June 25, 1901). Hall's process varied little from that used in the present day for the production of the abrasive.

The next difficulty lay in the type of furnace. The early type was a cumbersome firebrick structure which was often entirely destroyed in one run owing to the intense heat of the molten alumina (3700°F. being 600 degrees higher than the fusion point of the best firebrick). The later

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[1] Stansfield, A.: "The Electric Furnace," p. 302; McGraw-Hill Book Co., N.Y. (1914). (Gives description of Horry furnace).

iron or steel furnaces lined with firebrick or even carbon blocks were also destroyed. Serious damage was usually temporarily prevented (when the molten mass penetrated the lining and flowed against the steel shell) by turning a water hose onto the red spot. A. C. Higgins, who was then in charge of the electric furnace plant of the Norton Company, noticed that after the water had played on the spot it never became hot again during the run. It was then discovered that the cool fused bauxite was a very poor heat conductor. He, therefore, conceived the idea of chilling the entire furnace shell with water and allowing the cooled layer of fused alumina to act as the lining to the molten mass within. The first experimental run of his new furnace in 1904 was conducted with considerable trepidation, but was operated by Higgins and his foreman. It was found to be entirely satisfactory and with only slight improvements this type of lining has been used ever since.

Descriptions of the modern methods of manufacturing fused alumina follow those of historical interest described below.

Early American Processes

Jacobs' Process

The main points of commercial interest in this process (U.S. Pat. 659926, Oct. 16, 1900, filed May 1900) are the use of bauxite and the tempering of the fused alumina.

The detail of the electric furnace is shown in Figure 4[1]. The two outside pairs of electrodes are far enough from the furnace walls so that the latter are kept clear of the fused material; the hearth being left free to move up or down within the furnace. Before starting operations the hearth is raised to one inch below the electrodes and each pair placed in contact. The raw bauxite which has been previously calcined to drive off moisture and combined water, is charged into the furnace, and the current is switched on. The electrodes are then pulled apart, thereby setting-up an electric arc which fuses the bauxite. The alumina runs down into the hearth which is lowered at the rate of about two inches per hour. During the descent of the hearth the quiet pool of molten alumina cools and solidifies in the crystalline form, while most of the impurities in the raw material volatilize and escape through the opening on the top of the furnace.

According to Jacobs, the tempering of the fused alumina is brought about as follows:—

> The nature of the product may be varied by the slow or rapid cooling of the fused mass, so as to obtain a product of the same degree of absolute hardness, but of varying toughness, and consequently varying abrasive power, by the slow or rapid lowering of the hearth. The more slowly the product cools, the better defined will be its crystallization and the greater its toughness and abrasive power. The nature of the product may also be varied by agitating the mass while cooling, as by a poker or stirring rod inserted through the hole normally closed by a plug, and thus disturbing its natural tendency of crystallization, producing thereby a finer grain of crystalline structure than when the material cools without disturbance.

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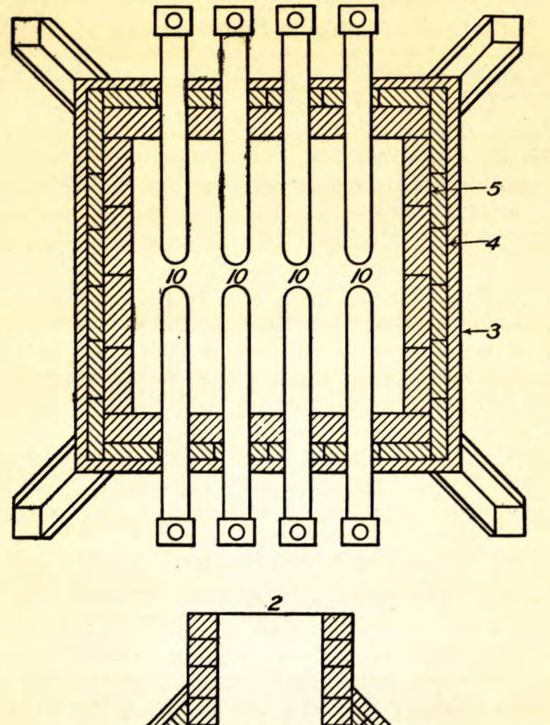
[1] Jacobs, F. B.: "Abrasives and Abrasive Wheels," p. 56; N. W. Henley Pub. Co., New York, (1919).



Reproduced from "Abrasives and Abrasive Wheels" (Fred. B. Jacobs)

Figure 4. Plan and section of Jacobs fused alumina furnace: 1, rectangular casing with sloping top; 2, opening for charging furnace and carrying away volatiles; 3, sheet-iron shell; 4, firebrick lining; 5, carbon bricks; 6, hearth (cast-iron); 7, hearth (powdered lime lining); 8, hearth carbon blowers; 9, screw to raise or lower hearth; 10, four pairs carbon electrodes; 11, cast-iron legs to support frame; 12, plugged opening to permit inspection and to stir contents with iron rod.

Hall's Process

C. H. Hall's experiments during 1900 appear to have been along lines similar to those of Jacobs. His work, however, for which he obtained a series of patents on the purification of aluminium ores, was entirely in connexion with the manufacture of metallic aluminium. His methods of treatment, although not a success as a source of that metal, are so near the present procedure—more so than Jacobs—for the manufacture of fused alumina, that some are briefly given below.

In his (Hall's) first patent (U.S. Pat. 677207, June 25, 1901, filed Dec. 19, 1900) bauxite is mixed with 5 to 10 per cent of coke and calcined to remove water and at the same time partially reduce some of the iron. If there is not enough iron in the ore more is added to the calcined material, also more powdered carbon, but not an excess which will reduce the alumina. The mixture is then placed in an electric furnace where during its operation the impurities are reduced and unite to form an alloy the bulk of which settles to the bottom. After cooling, the mass is broken up, the iron alloy button removed and the iron particles separated out from the mass by means of an electro-magnet. This method of rendering the iron magnetic and its subsequent removal, solved one of the early difficulties in connexion with the manufacture of a pure aluminous abrasive.

In another of Hall's patents (U.S. Pat. 677208, June 25, 1901, filed Feb. 2, 1901) he substitutes the coke for powdered aluminium or one of its alloys (ferro-aluminium) as the reducing agent for the impurities in the bauxite. The advantages claimed are that the exothermic reaction of the aluminium causes considerable heat, thereby conserving the electrical energy; also the violent evolution of gas caused by the loss of carbon is avoided.

Early European Processes.

Hasslacher's Process

This appears to be the first recorded process (German Pat. 85021, Nov. 20, 1894) for the then comparatively large-scale product of fused alumina. Native emery is used as the source of the alumina. Emery varies considerably in composition and may contain 15 to 40 per cent iron oxide and 50 to 70 per cent alumina, but the best material, which is high in alumina, is obtained from Greece. The composition and occurrences of emery will be found in Part II of this series of reports on Abrasives.[1]

Either finely powdered emery or dust from the emery grinding mills, is mixed with a sufficient quantity of coke to reduce the iron present into the metallic state, which melts during the operation and runs together in lumps. The mix is charged into an H-shaped electric furnace lined with firebrick (Figure 5), the top part being the container through the sides of which the electrodes protrude to within two inches of each other; the bottom part being a hollow chamber. There is a round opening in the bottom of the container covered with a fusible plate (such as glass).

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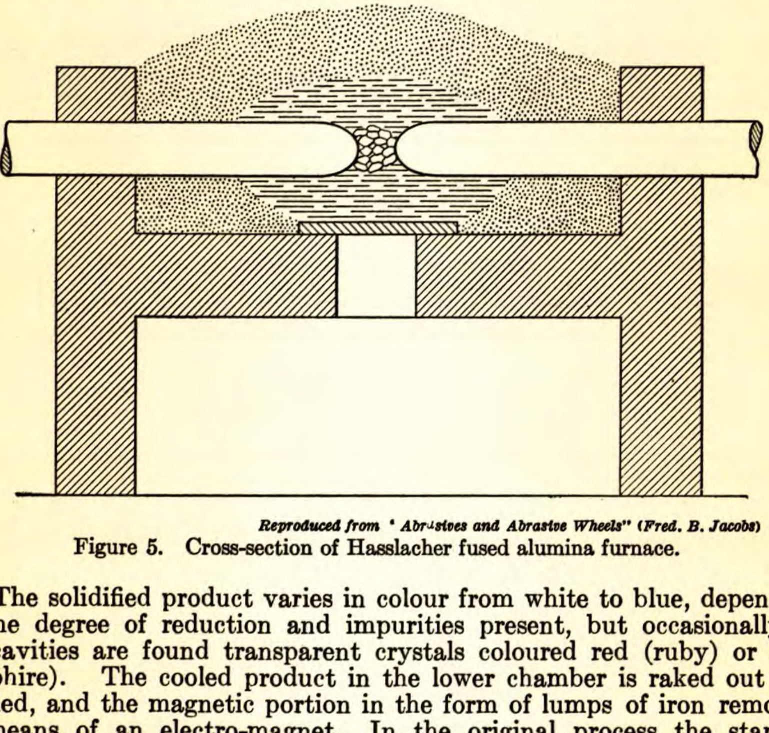
[1] "Corundum and Diamond"; pp. 36-40.

The furnace is charged from the top and the small gaps between the points of the horizontal electrodes are filled with a conducting layer of coke, after which the furnace is completely filled and heaped up. When the alternating current is turned on the coke becomes white hot and fuses the emery, thus soon forming a mass of molten emery round the arc. The progress of the reduction of the iron oxide is indicated by the burning of the carbon monoxide gas that escapes through the cracks in the furnace walls as well as in the charge. As soon as the glass plate fuses the molten emery runs down through the opening and is collected in the hollow chamber below. When the flow ceases a fresh charge is allowed to descend by breaking the solid crust on top with iron bars. This cools down and solidifies the molten mass round the opening on the floor and causes the hole to close which does not reopen until the surrounding part of the charge has again melted; the process is, therefore, a continuous one.



Reproduced from "Abrasives and Abrasive Wheels" (Fred. B. Jacobs)

Figure 5. Cross-section of Hasslacher fused alumina furnace.

The solidified product varies in colour from white to blue, depending on the degree of reduction and impurities present, but occasionally in the cavities are found transparent crystals coloured red (ruby) or blue (sapphire). The cooled product in the lower chamber is raked out and crushed, and the magnetic portion in the form of lumps of iron removed by means of an electro-magnet. In the original process the starting current used was about 300 amperes and 110 volts but during operations the voltage was reduced to 50.[1] The finished abrasive is said to be almost free of iron and compares favourably in purity with the best natural corundum and is better crystallized, but lacks abrasive temper. It was, at one time used in America, but after the advent of Jacobs' product, the process was discontinued. A patent was, however, taken out in 1915 (discontinued later) whereby the abrasive produced can be improved.

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[1] Haenig, A.: "Emery and the Emery Industry" pp. 35–38 (Trans. from the German by C. Salter); Scott, Greenwood & Son, London (1912).

Dollner's Process

In another German process invented by D. G. Döllner (Germany, Pat. 97408, Feb. 28, 1897) a mixture of powdered aluminium and various metallic oxides is ignited and react exothermically, owing to the extremely high combustion temperature of aluminium, resulting in the formation of fused alumina together with the metals of the oxides, originally added. If heavy metallic oxides are used, the alumina and the metals separate in the molten condition, so that on cooling, two distinct layers are obtained. The crystalline alumina produced by this method is claimed by the inventor to be so exceptionally hard that it can take the place of diamonds in drill crowns.

Werlein's Process

Although there does not appear to be any record of production as the immediate outcome of Ivan Werlein's patent, his addition to his original patent is of historical interest in that he was the first to suggest the use of calcined bauxite as the source of the alumina. A translation from the French is accordingly given below.[1]

The following is a 1st addition dated July 6, 1895.

Patent No. 233996. Dated November 11, 1893.
Issued to Mr. Werlein, for a process of hardening aluminous materials by electric fusion.

I have described in the patent a process of hardening aluminous materials; experience has led me to make several improvements in my system by which I am enabled to obtain a product superior in hardness to emery and to the various natural corundums, and one which is capable of being substituted for them in all their applications.

This product is obtained by the fusion of aluminous materials specified in the patent and particularly *bauxite*, by means of any furnace of high calorific intensity.

To prevent blows, the material is previously dehydrated in an ordinary furnace.

Under these conditions, the product is obtained in the form of a compact scorified mass, consisting of an aggregate of crystals of corundum, combined and entangled in such a way that they present no possible cleavage.

A micro-chemical examination reveals also a very appreciable proportion of microscopic dodecahedrons of crystallized carbon, the presence of which explains the exceptional hardness of the product.

The product thus obtained and suitably cut, may be used in the place of black diamonds.

In the state of powder or agglomerated into wheels, it may be employed for grinding, dressing and polishing metals, glass and crystals, by lapidaries, and, generally, with great advantage for all the known uses of emery and similar hard materials.

What I claim by the present addition is the improvement which I have made to the system of hardening aluminous materials by innate fusion, principally characterized by the employment of *bauxite*, in preference, as the aluminous material, as well as the resulting product, as described above and for the purpose specified.

MANUFACTURE OF FUSED ALUMINA

American Methods for Manufacturing Regular Fused Alumina

A brief outline of the manufacture of aluminous abrasive, which is also known as fused alumina or artificial corundum, is as follows:—

The bauxite is calcined, crushed, and mixed with coke and iron borings. It is then loaded into a water-cooled bucket or cylindrical iron shell furnace into the top of which is suspended carbon electrodes. The charge is

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[1] Arts Chimiques, vol. 86, series 3, Class 14, Sub-class 1, p. 106 (1893).

subjected to the intense heat of the electric arc for about 24 hours, which melts the mass. After cooling, the ingot of fused alumina is broken up, the button of ferro-silicon removed and the alumina is further crushed and pulverized. After magnetic impurities are removed it is finally graded into various sizes of grains required by the trade. A more detailed description of action during operations is given below.

Furnace

The usual type of furnace, invented by A. C. Higgins (U.S. Pat. 775654, Nov. 22, 1904) consists of a movable iron hearth or pan fitted with wheels and containing a layer of pitch and carbon. A conical iron cylinder fitted with an external water-cooler system rests upon this lined hearth. The whole furnace is wheeled on trucks below electrodes which can be lowered into the furnace. This is an improvement on the original Higgins patent in which the electrodes were stationary and the furnace itself raised or lowered by means of a plunger. In some plants the furnace is protected by a casing provided with openings through which the charge can be shovelled. A sketch of the present type of furnace is shown in Figure 6. The Otis Hutchins furnace (U.S. Pat. 1310341, July 15, 1919) consists of an iron bucket which is water-cooled in similar manner to the Higgins, the bottom of the bucket being lined with pitch and coke. It also rests on rails to allow free circulation of water under the bucket

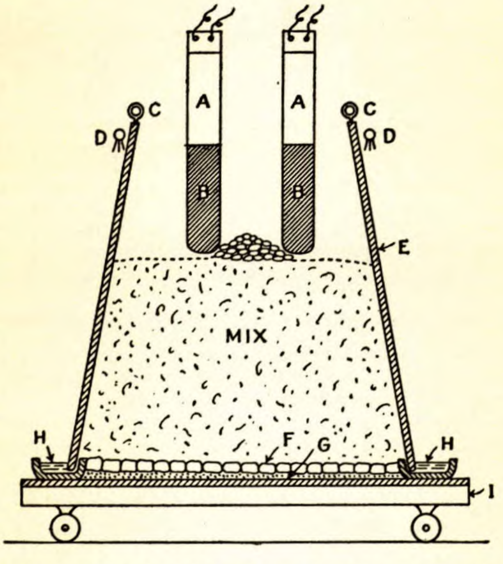

Figure 6. Cross-section of Higgins shell, water-cooled, fused alumina furnace: A, sheet-iron covering carbon electrodes; B, asbestos paper covering bottom of electrodes; C, lifting rings; D, water sprays; E, steel bell-shaped cylinder; F, base made of broken carbon electrodes resting on bauxite dust G; H, water trough; I, base mounted on wheels.

(Figure 7). After the molten mass has cooled the bucket is lifted up and the ingot dumped out, whereas in the Higgins type the iron cone is raised leaving the ingot resting on the hearth, but in both cases the whole furnace is previously wheeled away from under the electrodes. The electrodes are massive, rectangular carbon bars, about 6 feet long, with water-cooled heads. They are suspended from above into the furnace and can be mechanically raised as the furnace becomes filled up with the charge. (*See* Plate VII).

A regulator device set for a given current automatically raises or lowers them into the mass according to the current variations above or below the fixed current. Owing to the intense heat and action of the molten alumina, the carbons would be rapidly eaten away, but are protected to some extent either by a short iron casing above, with asbestos paper below, or by a coating of refractory cement held in place by wire netting. Even with this protection they last only 4 or 5 heats. Graphite electrodes would last longer, but are much more expensive.

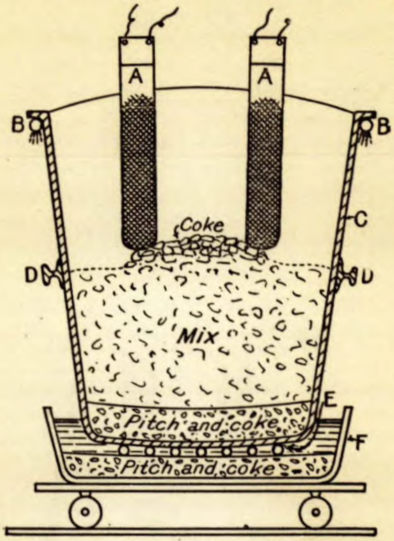

Figure 7. Cross-section of Otis Hutchins bucket, water-cooled, fused alumina furnace: A, cement-covered, movable carbon electrodes; B, water sprays; C, iron bucket with solid bottom; D, lifting and dumping handles; E, loose rods placed under bucket to allow free circulation of water; F, iron base carriage fitted with wheels.

The Charge and Functions of the Various Ingredients

Bauxite. Bauxite is an earthy mineral and varies considerably in appearance and chemical composition, its combined water ranging from 12 to over 30 per cent. It should contain at least 50 per cent alumina, not more than 6 per cent silica and under 3 per cent iron. High iron means more reducing required and consequently less alumina, and high silica requires too much iron. All commercial bauxites contain 1 to 3 per cent oxide of titanium, the presence or absence of which plays an important part in the physical properties of the final product.

The ore comes from several countries, amongst which are British Guiana, France, United States, Italy, Austria, Russia, and others; that from the first-named is the best and purest, but is expensive. These bauxites range from dark red to pale yellow in colour, many of them possessing a spotted or nodular appearance. Most of the United States bauxites, particularly those from Arkansas and Georgia, are trihydrates containing approximately 30 per cent water, but the Missouri material is a monohydrate containing 12 per cent water, 2 per cent iron oxide, and 6 per cent silica.

The crude bauxite is first broken up in jaw crushers, further crushed to about ½ inch and then calcined at about 2,000°F. in a rotary calciner to drive off the combined water, leaving a material which should contain 80 per cent alumina, or over. This preliminary calcination not only considerably raises the grade of the ore, but also conserves electrical energy and prevents complications in the furnace that would otherwise take place if the raw material were used. Before the other ingredients are added a very careful analysis is made of each batch of calcined bauxite in order to determine the exact proportions of coke and iron required.

Coke. A foundry coke is used to reduce the impurities to the metallic form. If too little coke is added part of these impurities will not be reduced and an impure low-grade abrasive will result; if too much is added some of the alumina will be reduced to aluminium carbide, which on exposure to the air will disintegrate and render the alumina valueless as an abrasive.

Iron. The iron is conveniently added in the form of borings. It attacks the silicon reduced by the coke forming a magnetic ferro-silicon containing less than 15 per cent silicon; it also renders the other reduced impurities highly magnetic. These impurities, a part of which is suspended throughout the mass of the fused alumina, can, therefore, be easily extracted by means of an electro-magnet after the crude abrasive has been crushed into grain. The bulk of the ferro-silicon runs together in the form of a "button".

All these ingredients are kept in storage bins and mechanically conveyed to the weighing bins from which the proper proportions are conveyed to the revolving mixers.

The proportions of the various ingredients in the charge depend upon the chemical analysis of the calcined bauxite and to some extent on the type of the fused alumina to be produced. A typical charge might be: calcined bauxite, 80 per cent; iron borings, 16 per cent; coke, 4 per cent by weight. The manufacture of the special types of aluminous abrasives, in which natural corundum or pure alumina are used in the place of bauxite, is discussed later.

The Operation of the Furnace and Products

The Preparation and Building of the Charge. In the Higgins or cylindrical steel shell type of furnace, the bottoms upon which the shell rests are prepared before each heat, as follows: A layer of bauxite dust is placed on the floor of the iron ring base, and upon this sections of old carbon electrodes are laid like bricks and cemented together with pitch. In some cases the bottom is built up with a mixture of pitch and coke to a thickness of a foot, and on the top of this a layer of bauxite dust is sometimes sprinkled.

The base is then wheeled along its tracks into the furnace room and under the electrodes. In the bucket furnace, the bottom part of the bucket is filled with pitch and coke with a protecting layer of bauxite dust.

After the furnace has been placed onto the prepared base by means of overhead travelling cranes, the previously mixed charge is then shovelled in to a depth of 18 inches to 2 feet and the electrodes lowered to just clear the top of the mix. A line of fine coke is then placed between the electrodes to act as a conductor for the current, but soon after the current has been switched on, the bauxite which fuses, forms its own conductor. When the first charge of the mix is fused, more mix is added and the electrodes gradually raised; this process is continued until the furnace is filled with the molten mass. This takes from 24 to 36 hours depending on type of furnace, size of charge, and nature of abrasive being made. Fused alumina furnaces in operation are shown in Plate VII.

The Current. The furnaces are usually run on an alternating current of 90 to 100 volts and require from 450 to 550 k.w. per hour, with a separate transformer to each electrode. The internal heat produced is about 3500°F.

The Furnace Products. After the current is switched off the water is kept circulating around the outside of the furnace walls for another 3 to 6 hours. The water is then turned off and the furnace is allowed to cool for about 7 hours after which it is wheeled out. After further cooling the shell is lifted off, or with the bucket type of furnace the solid mass is dumped out. The pig or ingot which weighs from 8 to 10 tons is then allowed to cool for about a week before being broken up. The rate of cooling is one of the factors which govern the degree of crystallization and is controlled according to the type of abrasive required.

The ingot consists of a mass of fused alumina held together by iron oxide and some particles of ferro-silicon as well as the other reduced impurities. The latter in almost all cases lie between the crystal planes or as inclusions within the crystals and not dissolved in them. At the bottom of the ingot is a "button" of solid ferro-silicon weighing 2 to 3 tons. Any undecomposed mix is sent back to another furnace. The furnaces are run in groups of three, namely—operating, water-cooling, and cooling before dumping or unloading.

The analysis of a good regular aluminous abrasive after cleaning, should be within the following ranges:—

SiO_2, 1·0 to 1·5; Fe_2O_3, 0·5 to 1·0; TiO_2, 1·5 to 3·5 per cent;
Al_2O_3, balance but not under 95 per cent.

Considerable experience and skill are required for the correct manipulation of the furnace charge and control of heat necessary for the complete reduction and fusion as well as the rate of cooling of the solid fused mass. If reduction be carried too far the abrasive may become too pure and brittle, since 2 to 3 per cent of iron oxide, silica, or titanium dioxide increases the toughness of the product. Moreover, if the raw material is exceptionally pure, some of the alumina is likely to be reduced to aluminium carbide, which on exposure disintegrates and destroys the value of the product as an abrasive.

Special Fused Alumina

For certain kinds of grinding operations, particularly those requiring cool cutting, a slightly purer and more brittle aluminous abrasive is required. Consequently the ore must contain more alumina and less impurities, particularly titanium, than bauxite. Titanium, more than any other impurity, appears to have an important bearing on the abrasive characteristics of the product, making it hard and tough. The titanium contained in the ore cannot be economically eliminated during the production of the fused alumina. For this reason the impurer regular alumina containing titanium is tough and resistant to fracture. When incorporated into grinding wheels it, under certain conditions, is liable to become dull, break out of the bond without much fracturing and heat the work. On the other hand the pure and titanium-free abrasive during grinding operations, will continually fracture, thus presenting new and sharp cutting edges and without unduly heating the work.

This type of abrasive is manufactured by several processes on the American continent; one process uses a pure, white, amorphous alumina powder and another a high-grade natural corundum. The amorphous alumina product, which is the purest, is a white porous material; that produced from the corundum is light grey, massive, and consists of large crystals. Its physical or abrasive characteristics are between the former and the regular fused alumina.

Amorphous Alumina Process

This process was patented by the Norton Company, Worcester, Mass., (L. E. Saunders and G. N. Jeppson, U.S. Pat. 954808, April 12, 1910), but expired in April 1927.

Pure, white amorphous alumina, almost entirely free of the oxides of iron, silicon, and titanium, is charged rapidly into an electric furnace provided with graphite instead of carbon electrodes. On account of these electrodes and rapid charging, the fused product undergoes but little reduction, possesses a crystalline, porous structure, and the formation of the injurious aluminium carbide is reduced to a minimum. However, the utmost care is necessary in the proper control and manipulation of the furnace. The ingot of fused alumina, which is almost pure white, is full of minute pores and perforations caused by small quantities of vapour from the alkali originally used in the preparation of the amorphous alumina. The porosity is further increased by the addition of the proper proportion of soda to the charge.

After being sufficiently cooled the ingot is crushed and then subjected to an oxidizing roast to remove any traces of aluminium carbide as well as to improve the bonding qualities of the abrasive.

An analysis of this finished abrasive having the trade name of "No. 38 Alundum" or "White Alundum" is as follows: Al_2O_3, 99·64; SiO_2, 0·20; Fe_2O_3, 0·16; CaO and TiO_2, nil.

Bonded into wheels it is used for grinding special steels, cutter, and general precision work. When made into vitrified wheels it becomes brick red in colour and is somewhat similar in appearance to the vitrified wheels made from natural or fused corundum, but in the silicate wheels, which are not subjected to such intense heat this special alumina retains its natural white colour.

Natural Corundum Process

In this process any pure natural corundum under 0·2 per cent titanium oxide can be used. At present the Zoutpansberg district, Transvaal, South Africa, is the source of supply. An analysis of the ground South African corundum used in the above process is as follows: Al_2O_3, 91·1; SiO_2, 4·5; Fe_2O_3, 2·2; TiO_2, 0·1; H_2O, 2·0 per cent. The Canadian corundum, such as was produced from Craigmont, Ontario, and vicinity, between 1900 and 1921, is, however, considerably purer and contains on the average: Al_2O_3, 96·9; SiO_2, 1·0; Fe_2O_3, 0·9; TiO_2, 0·02; H_2O, 1·1 per cent; while the blue corundum from Dungannon township, Ontario, contains over 98 per cent alumina.[1]

The process is patented by the General Abrasive Company, Niagara Falls, N.Y. (H. A. Richmond and R. Macdonald, U.S. Pat. 1413785, April 25, 1922), and was also used (until 1928) by the Abrasive Company at its plant in Hamilton, Ontario.

The corundum is broken up to a half inch or less and mixed with a sufficient quantity of iron borings and steel chips to make the total quantity of iron in the charge about three times the amount of silica present, so that the resulting ferro-silicon will be magnetic. Enough pulverized coke is added in order that, with the carbon supplied by the electrodes and furnace bottom, most, but not all, of the silica and iron oxide in the ore will be reduced at the temperature of the furnace.

It is claimed that by this method the formation of the objectionable aluminium carbide caused by over reduction is avoided.

The ordinary type of furnace and electrodes are used and the mixed charge is fed in slowly to ensure nearly complete reduction of impurities and uniformity of product. When a sufficient quantity has been melted, the electric current is shut off and the mass allowed to cool slowly within the furnace so as to produce large and well defined crystals. The cooled mass is then broken up, graded into grain, and the impurities removed by an electro-magnet and other mechanical means.

An analysis of the finished grain is as follows: Al_2O_3, 98·5; SiO_2, 0·8; Fe_2O_3, 0·5; TiO_2, 0·2 per cent.

The main uses for the above when formed into grinding wheels are for surface, cutter and knife grinding; automatic cylindrical grinding, etc. The vitrified wheel is brick red in colour similar to that of the natural corundum or the amorphous alumina products.

Retreatment Process

Some manufacturers treat a mixture of fused alumina fines, low-grade alumina removed in the early stage of hand-picking the crude product, and certain portions of their magnetics and electrostatic machine products obtained during the preparation and purification of the grain. These ingredients are re-melted in a manner similar to that used for the natural corundum and the product is similar in appearance.

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[1] Eardley-Wilmot, V. L.: Abrasives, Part II, "Corundum and Diamond", Mines Branch, Dept. of Mines, Can., pp. 1-20 (1927).

Other Methods of Varying the Abrasive Temper of Fused Alumina

The regular and types of special aluminous abrasive already described are now being manufactured on a considerable scale. In addition to these there are a number of patented processes, many of which are still in use but to a smaller extent. The essential differences lie in the degree of purity and the crystalline structure resulting in varying degrees of toughness, hardness, and method of fracture—namely, abrasive temper. These range between the almost chemically pure, brittle and porous, white "alundum" and a dense tough, very dark-coloured, comparatively impure product. Brief descriptions of some of these processes and products serve to illustrate some of the different methods whereby the abrasive temper of fused alumina can be varied.

Magnesia Process

Bauxite and magnesia are calcined and then mixed together with enough carbon to reduce most of the oxides of iron and silicon, a typical charge being 100 parts of calcined bauxite, 15 parts calcined magnesia, and 6 parts carbon. These are treated in the ordinary type of electric furnace, but the temperature is kept relatively low so as to reduce the above-mentioned oxides without affecting the magnesia and alumina. After cooling, the ferro-silicon formed is removed. The magnesium content of the finished product affects its toughness but should not be more than 25 per cent. (U.S. Pat. 1001497, Aug. 22, 1911, T. B. Allen, Carborundum Co.)

Boric Acid Process

By adding boric acid to the above alumina—magnesia process, the product is increased in brittleness and hardness. (U.S. Pat. 1001570, same date and assignee.) In another process calcined bauxite is mixed with 10 per cent of borax, a little chromite, and 3 per cent of carbon.

Titanium Process

Several patents were taken out between 1909 and 1911, by the leading manufacturers, in which titanium and iron are added to the pure alumina: (a) alumina and rutile; (b) alumina, silica, and titanium oxide free from iron; (c) alumina, titanium oxide and iron oxide but no silica. The last-named gives a blue-black product, which on account of certain physical properties is specially suited for making abrasive papers and cloths.

Strontium Oxide Process

Small fused alumina crystals can be made by the addition of strontium oxide to the charge. A typical charge consists of 300 parts aluminous waste from a previous run, 170 parts calcined bauxite, and 30 parts strontium oxide. The main use of the abrasive so produced is for coated papers and cloths. The normal product consists of comparatively large, smooth crystals which do not have the necessary roughness for ideal adhesion with the glue, but with the smaller crystals this roughness is accentuated. (U.S. Pat. 1339344, May 4, 1920, Otis Hutchins, Carborundum Co.)

Other Oxides

Modification of the abrasive temper of the fused alumina can be brought about by the addition of several other oxides besides those just mentioned. Some of these which have met with success are the oxides of silicon, iron, calcium, and others.[1] Any one or a combination of these produces a slightly different effect on the physical properties of the abrasive. As insufficient coke is added to the charge to reduce these oxides completely, they are present in the molten mass as silicates of the various metals originally added.

Alkali Process

For some types of abrasive it is necessary that they should be free from iron and titanium, but in the ordinary process the addition of carbon does not affect a complete reduction of the oxides of these metals—particularly the latter.

However, a preliminary roast with an alkali compound leaves these impurities in a segregated state so that they can be finally extracted with an acid. A typical charge consists of adding about 50 pounds of sodium and potassium carbonate to each ton of bauxite having approximately a composition of Al_2O_3, 54·8; SiO_2, 4·5; Fe_2O_3, 6·2; TiO_2, 4·0; and combined water, 30·5 per cent. On calcining at 1,000°C. the water is removed and the alkali combines with the oxides present forming easily soluble silicates. The product is mixed with about 5 per cent of coke and fused in the electric furnace. After fusion the impurities remain in the form of laminæ among the molten alumina crystals thereby weakening them and modifying their abrasive qualities. The pig is then broken up and treated with a hot solution of dilute (10 per cent) sulphuric acid for about 6 hours. (U.S. Pat. 1402714, Jan. 3, 1922, C. J. Brockbank, Abrasive Co.). A somewhat similar result can be obtained by the addition of the mineral cryolite (Na_3AlF_6).

Kaolin Process

Kaolin is mixed with carbon in the charge so as to reduce the silicon but not the aluminium. The fusion can also be facilitated by adding a base metal or ore such as iron or manganese which alloys with the silicon and makes the reduction more complete. The iron silicide so formed runs to the bottom and can be tapped at intervals. By altering the quantity of carbon in the charge, varying amounts of unreduced silica will remain in the product forming an alumina-silica mixture, ranging from 5 to 35 per cent silica of varying degrees of abrasive qualities. (U.S. Pats. 906338, 906339, 906172, 906173, Dec. 8, 1909, F. J. Tone, Carborundum Co.)

Rapid Cooling Processes

Rapid cooling of the molten alumina causes fine crystallization thus making a dense, hard and tough abrasive.

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[1] Norton Company; "Grinding", p. 25.

The molten and highly fluid alumina is tapped out in small masses by means of a tapping spout and quickly frozen, thereby producing a dense fine-grained product. The average grain size is about one-fifth that of the regular abrasive and makes it more resistant to fracture than the coarse-grained material. (U.S. Pat. 1192709, July 25, 1916, F. J. Tone, Carborundum Co.)

The molten alumina is tapped off from the furnace in a thin stream into a mould where it can cool rapidly. The fused material can be poured in successive layers into the same mould after each layer has solidified. The product is said to be homogeneous and substantially free from reduction impurities. (U.S. Pat. 1226892, May 22, 1917, H. T. Kalmus, Exolon Co.)

Very fine-grained crystals can also be produced by pouring the white-hot liquid alumina directly onto a cooled cast-iron plate so as to chill the alumina rapidly in a thin layer.[1]

Retreatment Process

The regular prepared grain is sometimes purified to a higher degree by fusion in the presence of sufficient carbon so as to cause a further reduction of the contained impurities. (U.S. Pat. 1310342, July 15, 1919, Otis Hutchins.)

Production of Fused Alumina from Materials other than Bauxite

Besides the use of natural corundum and amorphous alumina, fused alumina can be produced from metallic aluminium or from other minerals containing a sufficiently high percentage of aluminium.

Metallic Aluminium

In the early days of the production of fused alumina, the abrasive was obtained from the metal by several processes, two of these patented by Döllner in 1897 and Hall in 1901 are described under "Historical Processes" and some European processes will be referred to later.

A process which appears to be very similar to that of Hall was patented five years ago by T. B. Allen of Hamilton (U.S. Pat. 1448586, March 13, 1923) in which he substitutes metallic aluminium for coke as the reducing agent thereby obviating the possibility of forming objectionable aluminium carbide. With a calcined bauxite analysing Al_2O_3, 88·0; SiO_2, 5·0; Fe_2O_3, 2·5; TiO_2, 4·0; and H_2O, 0·5 per cent, he recommends the following proportions of ingredients: calcined bauxite 78, aluminium powder 12, and iron borings 10 per cent by weight. The charge is fused in an electric furnace in the usual manner.

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[1] Norton Company; "Grits and Grinds", p. 6 (1927).

Emery

Before the introduction of bauxite, emery was used but the abrasive was unsatisfactory in many respects. It is claimed, however, that even impure American emery can be advantageously used if magnesia and titanium oxide are added to the charge in their proper molecular weights so as to form eutectics with that of the magnesia already in the ore. The product after fusion is said to be a fine-grained, hard crystalline alumina, the spaces between and surrounding the individual crystals being filled with aluminates and titanates of magnesium. (U.S. Pat. 1149064, Aug. 3, 1915, H. T. Kalmus, Exolon Co.)

Beryl

Beryl is a green mineral, usually occurring in long hexagonal prisms having a formula $Be_3Al_2\ (SiO_3)_6$ and contains 19 per cent Al_2O_3. A typical charge for this process is as follows: 100 parts calcined bauxite; 75 parts beryl; 12 parts coke to reduce the oxides of iron and silicon; 50 parts of iron oxide to more readily remove the reduced silicon and titanium. The beryl gives the product an improved crystallization; the toughness decreases with the increase in the beryllia, but the hardness proportionately increases. The product contains about 89 per cent alumina and 7·5 per cent beryllia. (U.S. Pat. 1001571, Aug. 22, 1911, T. B. Allen, Carborundum Co.)

Nepheline Syenite

Fused alumina can be obtained by treating nepheline syenite in a water solution of sulphur dioxide, when all the sodium, potassium, and some of the silicon will be dissolved. By a series of precipitations and filtrations, aluminium silicates are separated out and are then calcined and fused in an electric furnace. (U.S. Pat. 1234905, July 31, 1917, H. T. Kalmus.)

Garnet

A process has been patented whereby the waste garnet fines are fused in an electric furnace with the production of alumina and ferro-silicon. Almandite garnet contains approximately 40 per cent Al_2O_3; 37 per cent SiO_2, and 19 per cent Fe_2O_3. The mix consists of about 18 per cent of powdered coke with garnet and the charge is fed into a special arc furnace using an alternating current with low voltage. The garnet fuses at about 1,260°C. During the reducing operation active ebullition occurs, considerable gas being driven off. After a short period the current is gradually increased until the furnace temperature reaches the fusion point of alumina (2,050°C.), this heat being held until ebullition ceases. The current is gradually lowered to permit slow crystallization of the alumina. The breaking up of the pig and removal of the ferro-silicon is the same as in the case of the ordinary methods of manufacture (U.S. Pat. 1192394, July 25, 1916, J. Davenport.)

European Processes for Manufacturing Fused Alumina

The usual method of manufacturing fused alumina is very similar to that practised on the American continent, but with few exceptions the European products are of inferior quality. Other processes both past and present follow:—

Sulphur-Aluminium Process

A process somewhat on the same lines as Döllner's was used in France about 1903 and is as follows: Approximately equal parts of aluminium dust, pulverized fused borax and flowers of sulphur are mixed together in a crucible and calcined with a mixture of magnesium and barium dioxides, whereby such a high temperature is attained that partial fusion of the resultant alumina takes place. After cooling the mass is broken up and treated with dilute ammonia. The aluminium hydroxide resulting from the decomposition of the aluminium sulphide is removed by means of hydrochloric acid. The residue contains globules of aluminium, brown flakes of boron, and white crystalline alumina. After mechanical removal of the metallic globules, the boron is dissolved with nitric acid, leaving the pure crystalline alumina.[1]

Thermit Process

A crude form of fused alumina, having the trade name of "Corubin," is picked out of the slag produced in the manufacture of chromium by the "Thermit" process; it is composed mainly of alumina and chromium. Until comparatively recently a considerable tonnage of this French material was sold to the United States grinding wheel manufacturers, and large quantities are used in Europe particularly in the optical industry for glass grinding.

The Haglund Process

This process under patents by T. R. Haglund was introduced several years ago in Sweden. It was developed experimentally in Germany and is now being employed commercially in Italy.

Calcined bauxite, coke, and a heavy metallic sulphide (preferably pyrrhotite) are treated in an electric furnace, resulting in the formation of aluminium which immediately reacts with the iron sulphide forming aluminium sulphide.[2]

$$Al_2O_3 + 3C + 3\ FeS = Al_2S_3 + 3\ CO + 3\ Fe.$$

At the prevailing temperature of the furnace this sulphide dissolves the excess alumina forming a sulphide-oxide slag which is very fluid and easy to tap.

This slag, which is obtained as a continuous operation by tapping the furnace, carries a considerable quantity of iron containing all the silicon of the raw material. The silicon separates readily and the alumina crystallizes out while the slag is solidifying when the sulphide can then be separated from the oxide crystals by a simple operation. By regulating the rapidity of the cooling of the slag, crystals of different sizes can be obtained.

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[1] Haenig, A.: "Emery and the Emery Industry"; p. 34, (Tr. from German by C. Salter), Scott, Greenwood & Son, London, (1912).

[2] Haglund, T. R.: Ind. and Eng. Chem., p. 67, Jan. 1926.

When sufficiently cool, the slag is crushed and treated with water which decomposes the sulphide with the formation of sulphuretted hydrogen (which can be collected as a by-product and utilized) and aluminium hydrate:—

$$Al_2S_3 + 6H_2O = 2\,Al(OH)_3 + 3\,H_2S.$$

The residue contains a mechanical mixture of crystallized oxide and hydrate of aluminium with small quantities of the sulphides of the impurities, such as iron and titanium. The products in this mixture are then separated from each other by means of gravity system of classifiers, jigs, and tables. The hydrate is collected as a by-product which after calcining can be used for various purposes. The crystallized alumina is washed with warm sulphuric acid, dried, and graded into sizes for the abrasive market.

THE PREPARATION AND GRADING OF FUSED ALUMINA

Preparation

After the fused alumina ingot has been deposited on the floor of the furnace room it is first broken by causing a two-ton weight to drop upon it from the roof. The lumps are then further broken up with sledge hammers and the solid "button" of ferro-silicon removed. The material is next passed through a jaw crusher and over a picking-belt where impurities and low-grade alumina are taken out by hand and thrown into separate piles for further use or treatment. The alumina then passes over a series of rolls and screens till reduced to 6 or 8 mesh, when it is passed under an electro-magnet which removes the more highly magnetic part, including iron, unavoidably introduced from the crushers and rolls. The non-magnetics are roasted in order to render the non-magnetic iron content magnetic; they are then passed over a trough classifier with the addition of water to remove the dust or fines which are settled out in a series of tanks by elutriation, dried, and marketed as the "flour" grades. The classifier settlings go to a drier and thence over another magnetic separator, the clean non-magnetics from which go to the grading department where they are graded into about 20 different sizes as described in the grading of the silicon carbide grain. A composite flow-sheet illustrating the preparation and cleaning of fused alumina is given in Figure 8.

Grading

The grading of the grain is performed in exactly the same manner to that already described for silicon carbide. Photomicrographs of fused alumina are shown in Plate XIX A and B.

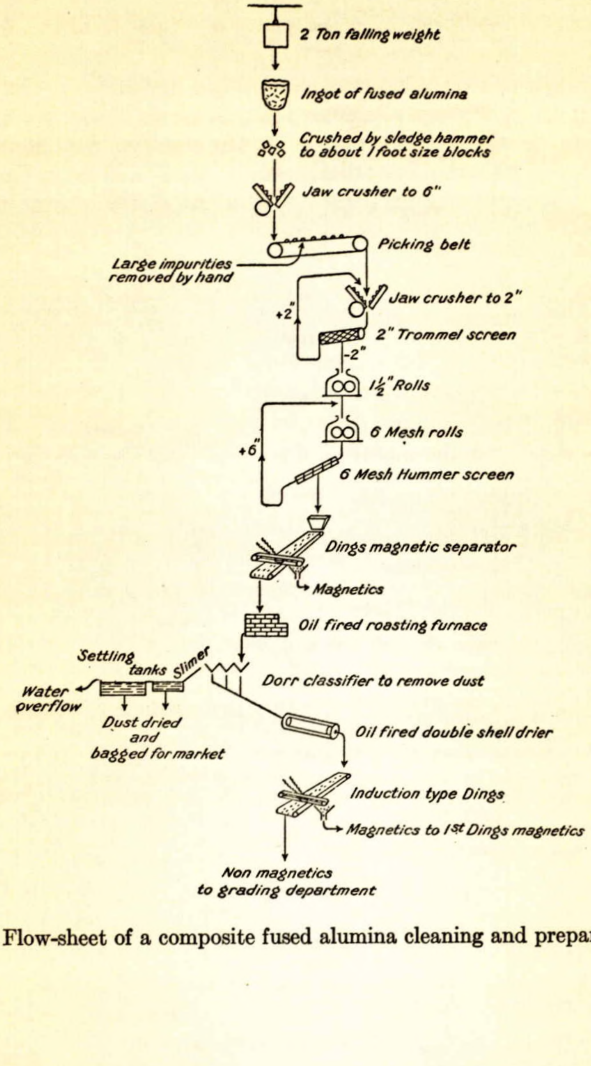

Figure 8. Flow-sheet of a composite fused alumina cleaning and preparation plant.

ARTIFICIAL ABRASIVE MANUFACTURERS

CANADA

The bulk of the artificial abrasives manufactured on the American continent is made in Canadian plants. The whole output is shipped in the crude state to the parent plants in the United States for crushing, cleaning, and grading, none of which is done in Canada. There are four companies in Canada with a total of five plants, three of which produce silicon-carbide and three fused alumina. The plants are near Niagara Falls, Ontario, and at Shawinigan Falls, Quebec.

The Canadian Carborundum Company at Shawinigan Falls, Quebec, is the world's largest producer of silicon carbide ("Carborundum"). At one time this plant also made fused alumina, but the company's Canadian production of this latter abrasive ("Aloxite") is now confined to the Niagara Falls plant from which a very large output is maintained. Both regular and special aloxite—the latter, a high-grade grey-white abrasive known as "Aloxite AA"—are made here.

The Norton Company at Chippewa, Ontario, three miles south of Niagara Falls, manufactures both fused alumina ("Alundum") and silicon carbide ("Crystolon") and is the world's largest producer of the former abrasive of which three types are made—regular alundum, 66 alundum, and 28 alundum. The last-named is a very pure and white product made from pure amorphous alumina.

The Exolon Company at Thorold, Ontario, seven miles west of Niagara Falls, is a large producer of silicon carbide ("Carbolon"). The production of fused alumina ("Exolon") was resumed in June, 1928, after a quiescent period.

The Abrasive Company has a fused alumina plant at Hamilton, Ontario, where it produces two grades of "Borolon", regular and S. B. The latter, a pure, grey-white material, was, until recently, made from natural corundum.

The methods of manufacture are similar to those already described. The individual operations, power and equipment used, and other details are in most instances closely guarded so that no details are being published.

The following tables give the Canadian production of silicon carbide and fused alumina, also the total consumption of the principal ingredients.

TABLE I

Canadian Production of Artificial Abrasives

—	1923		1924		1925	
	Tons	Value	Tons	Value	Tons	Value
		$		$		$
Silicon carbide............	12,660	1,382,747	15,207	1,773,864	18,033	2,194,496
Fused alumina............	32,201	3,620,497	29,822	3,170,204	27,592	2,992,306
Total.............	44,861	5,003,244	45,029	4,944,069	45,625	5,186,802

—	1926		1927		1928	
	Tons	Value	Tons	Value	Tons	Value
		$		$		$
Silicon carbide............	20,285	1,779,492	17,334	1,961,910	19,008	2,098,199
Fused alumina............	34,649	3,423,526	35,085	3,230,928	39,413	3,786,113
Total.............	54,934	5,203,018	52,419	5,192,838	58,441	5,884,312

TABLE II

Principal Ingredients used in the Production of Canadian Artificial Abrasives

SILICON CARBIDE[1]

Year	Coke		Sand		Sawdust		Salt	
	Tons	Value	Tons	Value	Tons	Value	Tons	Value
		$		$		$		$
1924...............	21,291	356,918	30,116	175,479	7,000	28,628	254	2,487
1925...............	20,434	361,825	33,528	196,204	7,010	23,757	410	4,433
1926...............	26,423	368,320	36,086	188,286	6,678	27,363	595	3,386
1927...............	24,661	313,456	34,843	171,470	6,907	26,890	447	4,522
1928...............	24,256	314,609	37,152	177,342	7,433	28,485	472	4,048

[1] Total number of furnaces now being used = 65.

FUSED ALUMINA[2]

Year	Bauxite		Coke		Iron		Electrodes	
	Tons	Value	Tons	Value	Tons	Value	Tons	Value
		$		$		$		$
1924...............	37,978	783,658	2,758	16,677	4,979	67,008	803	89,381
1925...............	33,066	691,993	2,865	16,877	4,913	60,886	830	99,715
1926...............	40,092	869,175	1,732	12,846	4,604	56,883	863	113,485
1927...............	35,528	757,710	3,271	23,705	3,322	42,333	894	120,792
1928...............	43,046	896,203	3,163	17,728	4,393	51,917	968	125,211

[2] Total number of furnaces now being used = 25.

UNITED STATES

As previously mentioned the bulk of the artificial abrasives is made in Canada and shipped in the crude form to the parent companies in the United States. Both silicon carbide and fused alumina are manufactured by the Carborundum Company at Niagara Falls, New York, also by the Federal Abrasive Company at Conniston, Alabama. Fused alumina is manufactured by the Norton Company and by the General Abrasive Company, both at Niagara Falls, New York. The crude furnace products are crushed and graded by these concerns. The Canadian crude products are treated also by the Carborundum Company at Niagara Falls, New York, by the Norton Company at Worcester, Mass., and by the Exolon Company, at Blazedell, New York.

The following table gives the total artificial abrasives produced from both the Canadian and United States plants.

TABLE III

Crude Artificial Abrasives Sold, Shipped, or Used, from Manufacturing Plants in the United States and Canada, 1917-1928[1]

Year	Silicon carbide		Aluminium oxide		Metallic abrasives		Total	
	Short tons	Value	Short tons	Value	Short tons	Value	Short tons	Value
		$		$		$		$
1917..........	8,323	1,074,152	48,463	6,969,387	1,125	93,703	57,911	8,137,242
1918..........	10,047	1,518,600	35,716	5,741,270	5,150	422,727	50,913	7,682,597
1919..........	28,435	3,380,151	19,723	3,811,498	2,360	274,200	50,518	7,465,849
1920..........	6,887	1,309,605	32,891	5,956,639	2,659	225,920	42,437	7,492,164
1921..........	2,707	475,336	7,325	1,318,771	3,167	202,040	13,199	1,996,147
1922..........	16,233	2,022,613	31,898	3,246,714	5,804	421,148	53,935	5,690,475
1923..........	21,149	2,786,929	51,391	5,378,926	8,229	612,140	80,769	8,777,995
1924..........	17,792	2,161,498	33,708	3,482,577	8,597	569,665	60,097	6,213,740
1925..........	24,112	2,493,756	53,253	4,714,562	11,165	780,612	88,530	7,988,930
1926..........	17,026	1,702,037	43,967	4,106,699	12,610	942,429	73,603	6,751,165
1927..........	26,289	2,603,571	50,973	4,516,637	13,364	839,683	90,626	7,959,891
1928..........	22,162	2,286,518	59,103	5,640,901	18,466	904,629	99,731	8,832,048

[1] "Abrasive Materials" Min. Res. United States. U.S. Bur. of Mines annual.

EUROPE

Although artificial abrasives are produced by about sixteen firms in Europe, the output from the majority is small and irregular and is largely for their own consumption, or is in the form of refractory materials. Their products, with possibly two or three exceptions, are inferior to the abrasives made on the American continent.

Silicon carbide is manufactured in five plants, one each in Germany, France, Norway, Sweden, and Czechoslovakia. The Norwegian producer at Eydehavn has the largest output. The product known as "Sika" is exported to a small extent to Canada and the United States and is said to compare favourably with the American abrasive. The French producer of silicon carbide at La Bathie has recently gained an important place in the European market; another important producer is located at Wessling, Germany.

Fused alumina is believed to be produced by three firms in Germany, two in France, and one each in Sweden and Switzerland. The Electro-Chimique de Mercus, France, is by far the largest producer, having plants at Mercus and also at Bonnerville, below the outlet of lake Geneva. Their abrasive, which is of good quality, known as "Boro-Carbone," constitutes over 50 per cent of the manufactured abrasive imports into America. A small quantity of fused alumina ("Abrasite") is also imported from Basle, Switzerland. "Achromine", which is a French product, is mainly used in Europe; other products being "Veral" from Laus, Germany, also "Dirubin" and "Redurit" from Wessling, Germany.

No statistics of the European production are available, but during the last two or three years the imports of these abrasives into Canada and the United States have fallen and are shown in the accompanying table.

Imports of European Artificial Abrasives into U.S.A., 1926–1928.

Country	1926		1927		1928	
	Short tons	$	Short tons	$	Short tons	$
France	2,884	191,340	1,568	100,991	1198·4	74,900
Germany	440	30,510	462	34,258	441·1	30,989
Norway	113	13,047	–	–	327·3	27,805
Sweden	–	–	2	150	–	–
Switzerland	–	–	–	–	0·2	28
United Kingdom	–	–	–	–	0·2	36
Totals	3,437	234,897	2,032	135,399	1,967·2	133,758

GRINDING WHEELS

The *grinding wheel* or abrasive wheel is recognized as a manufactured product, since the bonding of the grains is produced by artificial means, whereas in the *grindstone* the cementing is done by nature and the stone cut from natural beds. The grinding wheel is really a milling cutter with thousands of tiny teeth. Its action is one of cutting minute slivers by each grain while held firmly in the bond, and although they do not cut so deeply as a steel instrument they are nevertheless capable of cutting at a much greater rate of speed. The action of the natural grindstone is somewhat different since the grinding is mainly performed by detached grains held in place on the periphery of the wheel by means of water.

On various occasions the nomenclature of the somewhat unsatisfactory word "grinding wheel" has been discussed. The word "abrasive wheel" is sometimes used but, as described above, the action of the artificial product is more one of cutting than that of true abrasion, so a suitable name has not yet been found.

HISTORICAL

The first use of the natural grindstone is lost in obscurity, but the earliest records of the manufacture of artificially made grinding wheels date back only about seventy years.

In the early days emery was the principal abrasive, and corundum was introduced in the early eighties. These continued in vogue until the commercial production of silicon carbide about 1893. The former grinding wheels were made to last rather than to cut rapidly, the slow cutting being, however, mainly due to the type of abrasive used.

To-day, vitrified, silicate, shellac, and rubber bonded wheels are made. A few historical details of interest concerning the earliest manufacture of these types of wheels are given below.

Some of the earliest moulded wheels were made in England from a mixture of emery and Sorel cement (oxide and chloride of magnesium). The first solid emery wheel is credited to Henry Barclay, England, in 1842.[1] The first rubber bond wheel made in the United States is attributed to T. J. Myall, Roxbury, Mass., who in 1859 took out several patents[2] for the processes of manufacturing solid wheels of a more or less flexible nature. These were formed by mixing emery with India rubber, gutta percha, sulphur, and olive oil. The New York Belting and Packing Co. in 1865 was the first large company to produce rubber bond wheels commercially and have made them continuously since that date.

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[1] Paper on "Grinding Wheels" read in 1878 before the Society of Arts, London, England, by A. H. Bateman.

[2] U.S. Pats. 22606, Jan. 11; 24039, May 17; 25747, Oct. 11, and 25841, Oct. 18, 1859.

Ceramic bonded wheels undoubtedly originated in the United States, and the first *vitrified wheel* appears to have been made by Thomas Nelson[1] of West Troy, N.Y., who in 1864 moulded a mixture of emery, clay, and flux into the required shape and subjected it to the proper heat to vitrify the mass. In 1867 the Northampton Emery Wheel Co. produced a wheel in which the abrasive was bonded with glue and clay. No heat was used and it was necessary to dry the wheel for a considerable period; thick wheels were made by gluing together thin ones. Japan varnish cement was perfected shortly after and wheels were made with "baking japan" by J. L. Otis[2], Leeds, Mass., in 1870. The mixture which consisted of emery, baking japan, boiled linseed oil with or without litharge, was moulded to form and baked in an oven. The Northampton company made this type of wheel until 1910.

Commercial production of the vitrified wheel started about 1871 when the Vitrified Wheel Co., Ashland (now Westfield), Mass., acquired Nelson's patents (1864 and 1866). About the same time in 1872 Swen Pulson also produced vitrified emery wheels. He was associated with F. B. Norton and F. Hancock, stoneware manufacturers of Worcester, Mass., who made the wheels in a pottery kiln.

Patents for the process using *silicate of soda* as a bonding material for making artificial stone was granted in England to Seimens in 1845, and to Ransome in 1857, but the idea does not appear to have been applied to grinding wheels until about 1868. About this time Gilbert Hart, an artificial stone manufacturer, of Detroit, was engaged in making window sills from a mixture of sand and silicate of soda. The sill business was not a success and the possibility of making grinding wheels by substituting emery for the sand was suggested. The first wheels were made by mixing emery with silicate of soda and clay, moulding and baking at about 500°F. The wheels were successful and the new business was established. In 1878, a friend having been killed by the bursting of a wheel, Hart invented a safety device in the form of a *wire web* inserted in the wheel during the process of manufacture.[3] The use of this web became very popular and was an important factor in the growth of the wheel business and is still used to some extent in the present day.

About 1876 Henry Richardson in his efforts to produce a wheel better adapted to the finer classes of work in his business of watch-tool manufacturing produced the first *shellac wheel*, the original experiments being conducted on top of a kitchen stove. Later, Richardson founded the Waltham Grinding Wheel Co., Waltham, Mass., and the first shellac bond wheels were marketed in 1880.

Although many improvements were made in the different classes of grinding wheels, no new types have been made with the exception of the comparatively recent introduction of synthetic resin bonds such as "Bakelite".

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[1] U.S. Pat. 44918, Nov. 1, 1864.
[2] U.S. Pat. 100659, Northampton Emery Wheel Co., March 8, 1870.
[3] U.S. Pat. 201778, March 26, 1878.

PRESENT STATUS

The grinding wheel is indispensable in modern industry and its application has now reached the stage where there is hardly any material upon which it is not directly or indirectly used. The wheel of to-day is made in every variation of grade, size, and shape so that it has completely revolutionized the art of the machinist. Precision and centreless grinding for example are now perhaps the most important machine shop practices, for without them the automobile and aeroplane engine and countless other standard mechanisms would be impossible. This, together with the general utility of the grinding wheel for rougher operations, makes an instrument without which modern industry could never have attained its present advanced stage. Grinding has supplanted the lathe and machine tools in many operations. The modern wheels containing silicon carbide or fused alumina abrasives are uniform in every respect and can be duplicated—both features being highly important factors in successful production.

It has been estimated that there are twenty million dollars worth of abrasive wheels sold annually in the United States.[1]

MANUFACTURE AND GENERAL USES OF GRINDING WHEELS

Variations in Grade and Grit

The grinding wheel consists essentially of an abrasive and a bond which holds the abrasive grain in place. There is a considerable variety in the type, hardness, toughness, and degree of fineness in the abrasive as well as in the nature, constituents, and the amount of the bond used. Moreover, grinding wheels are made by several entirely different processes and it is the almost infinite variety in the combinations of these grits, bonds, and processes which results in the numerous types of wheels suitable to every phase of modern grinding. They range from the hard, compact and tough wheel with hard tough grit and a high percentage of bond used for snagging heavy iron castings, to the open and porous wheel with a brittle abrasive and but little bond used for the coolest free-cutting work.

Although the many conditions mentioned above play an important part, the composition and percentage of bond, particularly in vitrified wheels, are the main factors that determine the "grade" (hardness or softness) of a wheel. With a high percentage of bond, the abrasive grain adheres with more tenacity to the wheel in operation and is not pulled out and is known as a "hard" wheel; in a "soft" wheel with less bond and more abrasive the grains are more easily freed, thus constantly presenting fresh grains. An ideal wheel is one in which the grain falls out or fractures at the precise moment—not before nor after it becomes dull—and this period depends entirely on the nature and hardness of the material that is being abraded.

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[1] Bolyea, B.: "Modern Grinding Wheels Lower Production Costs"; Abrasive Industry, June 1928, p. 166.

Processes of Manufacture

There are five different processes by which grinding wheels are made, viz.: vitrified, silicate, elastic or shellac, synthetic resin or Bakelite, and rubber. The vitrified bond has been found by practice to be the best for most grinding purposes as a greater range of grades can be obtained by this process than by any other.

Vitrified Process

The vitrified process produces an open porous structure which ensures rapid and free cutting, and having a very strong bond it is adapted for nearly all classes of work. Approximately 75 per cent of the wheels now used are made by this process. However, solid wheels more than 36 inches in diameter cannot be vitrified because of the danger of warping or cracking during the burning process.

Briefly, the process consists of mixing the bonds and grain with water in suitable mixers, pouring or ladling into moulds, drying, trimming to the approximate shape, and then burning in a ceramic kiln for certain periods at a carefully controlled temperature, during which time the bond is fused or vitrified. The final dressing to exact size, balancing, bushing, and testing are similar for all types of wheels. A detailed description of the process as employed on the American continent is as follows:—

The ceramic bonds consist of a mixture of fusible clays and feldspar. There are several kinds of clay used, the principal being Albany slip clay, ball clays, fireclays, stoneware clays, kaolin, and others. The slip clay and feldspar are used for fluxing, but the latter is not used in soft wheels; ball clay, besides being a good refractory, gives a good bond and tends to make a hard wheel. Fuller's earth is also used for soft wheels.

The *abrasive grains*, such as silicon carbide and fused alumina (also emery and corundum if used), which have been previously cleaned and graded into about 20 different sizes from 8 to 220 mesh, are usually elevated to the top floor of the wheel plant. They are kept in separate sealed containers or closed bins so as to exclude dust or oil which would prevent the proper adhesion of the grain with the bond. For convenience in mixing, the bonds for immediate use are also kept in closed bins on the same floor near the grain.

For proper *mixing* each of the bond and grain bins are connected by means of pipes or spouts to the floor below where each ingredient can be run into a counter-balance bucket which travels on rails along and below the entire length of the spouts. The exact proportions of the bonds and grain (which are closely guarded secrets of each manufacturer) are here weighed out and dumped into one of the hopper bins which are also connected by spouts with the main mixing floor below.

METHODS OF MOULDING

Two methods of *moulding* are employed—the *Puddled* method which consists of mixing with water into a slush and casting into moulds, and the *Pressed* method in which the mixture is moulded to form almost dry, and subjected to hydraulic pressure. A combination of both processes is sometimes used. A puddled wheel is considerably more porous than the pressed wheel. Further details are given below.

Puddled Method. The correctly proportioned ingredients from the floor above are run into a hemispherical mixing kettle provided with internal baffles (Plate VIII) in which they are agitated with the gradual addition of water until the mass becomes a thin paste. The mixing is continued for 1 to 3 hours according to the size of the mix until all the entrapped air is expelled, not more than 700 pounds being mixed at once, because of the danger of some air bubbles remaining which would result in weak spots in the finished wheel. When the agitation is completed, the tap at the bottom of the kettle is opened and the paste is allowed to flow into a series of moulds. These moulds consist of hoop iron rings, slightly larger than the required size of the finished wheel, and are supported on plates or "batts" and lined with heavy paper. The pouring is done carefully and slowly and the paste is stirred or hand-puddled with the ladle to exclude any air that might be entrapped.

For puddling of very fine grits such as in wheels used for glass bevelling, each mould is provided with a small mechanical stirrer having a worm thread that gradually raises the stirring arms through the wet mix in the mould at the rate of about 1 inch in 5 minutes until clear of the mix.

In the drying process, the moulds containing the wet sludge are roughly smoothed off, then placed in a dry room for two days without heat and then "spooned" (a spoon drawn lightly across the top to draw out the water). They are then sent to a drying-room and kept at about 120° to 150° F. for varying periods up to 8 days, according to size of wheel, though the very largest wheels now made have to be dried for several weeks. The green wheels are then sent to the "shaving" department.

Pressed Method. The previously weighed ingredients are sent to a barrel tumbler to which is added enough water to dampen. In some instances ammonium hydrate and an adhesive bond are also added. These are tumbled for several hours so as to thoroughly mix and surround each individual grain with the bonding mixture. The mix should be dry enough to hold its shape when the correct amount is evenly distributed into a thick steel mould of the exact size and design of the wheel. After carefully levelling off, a cover that snugly fits the bore of the mould is inserted and the whole is then placed under the ram of a hydraulic press and subjected to a pressure of 2,000 to 3,000 pounds per square inch (Plate XA). The type and grade of wheel required determines the pressure applied, the higher the pressure, the harder and more compact will be the finished wheel. The mould is then removed and the wheel dried in a hot-air chamber as in the puddled process, but the period is much shorter, being only about one day.

Wheels made by the pressed method are very compact but not necessarily hard. The method is more rapid and requires less skill than the puddled process, wheels do not have to be shaved, and almost the same variation of types of wheels can be obtained.

Combined Methods. The wet paste, such as used in the puddled process, is sometimes moulded and allowed to stiffen and remoulded in steel moulds fitted with base and cover plates and subjected to hydraulic pressure of 500 to 700 pounds per square inch. This remoulding and pressing however tends to separate the particles in one direction and compress them in another thus altering the texture of the mass. Better results may be obtained by subjecting the freshly moulded but drier paste to a pressure applied both from above and below.

SHAVING

After the "green" wheels obtained by some of the above methods have been thoroughly dried they are wheeled into the "shaving" room. The wheel is removed from its slab and placed on a revolving circular table. By means of special tools, the soft green wheel is dressed or shaved down to the required shape and size, but leaving enough to allow for shrinkage in the kiln and final truing; the centre spindle hole is bored at the same time (Plate IX B).

All the shavings are collected and stored to be used as reclaimed grain.

BURNING

The kilns are usually of the circular combination, up-and-down draught type such as are extensively used for the firing of pottery. Eight to ten fire-boxes extend radially inward at the base of the kiln, coal being the fuel most commonly used. The kilns vary from 8 to 18 feet in diameter and 30 to 60 feet high, the smaller ones being used for the small wheels. A secondary or interior dome-shaped structure is built within the kiln and is about 20 feet above the kiln floor where the wheels are stacked. The kilns are constructed so that the hot gases can freely circulate amongst the wheel stacks, down through vents in the floor, and finally escape up the narrow space between the inner and external walls. Some of the larger concerns have recently erected large continuous-chamber kilns, heated by producer gas. The waste gases from one chamber pass to other chambers and thus considerably reduce the amount of fuel consumed when separate kilns are employed.

After the blank wheels come from the shaving room they are placed in rings of fireclay called "saggers" which are covered top and bottom with fireclay tiles. Quartz sand, in which the wheels are evenly and solidly bedded, is used inside these saggers and all cracks are plugged with clay in order to prevent the flames reaching the wheels within. Two or three small wheels are placed in one sagger but those over 15 inches in diameter require one each. Wheels of 20 inches or over are packed in sectional saggers—three or more sections to a ring—and joints well sealed with clay. The saggers and their contents are then placed one on top of the other in the kiln until they almost reach the roof of the internal dome. The process is repeated until the kiln is filled with stacks of saggers (Plate IX A).

Considerable skill is required in packing or loading a kiln—each wheel must be bedded absolutely level in the sand, otherwise it will warp; all cracks in saggers must be carefully sealed; the spacing between the stacks must be such that the hot circulating gases will evenly distribute the heat and at the same time the stacks must be close enough to obtain the maximum load for the kiln. After completely filling, pyrometer cones are placed inside on a ledge opposite each inspection hole and the door is then sealed tight.

The heat must be applied very gradually and at a definite rate, uniformly and up to a definite maximum intensity. The duration of the time of the burning and "soaking period", and to some extent the temperature, depend on the size and type of wheels as well as the size of the kiln. For the larger kilns of 15 feet diameter or over it takes 3 to 4 days to attain the required temperature which ranges from 2,400°F. to 2,800°F. The temperature is kept constant for a certain predetermined period. This soaking period at maximum temperature is to ensure uniformity throughout all the wheels and varies from 3 to 24 hours. The kiln is then allowed to cool very gradually for 10 to 14 days. It is then unloaded, saggers removed, and the wheels are sent to the finishing department. The whole cycle of loading, firing, cooling, and unloading takes about three weeks but for the small 8-foot kiln this can be done in about one week.

The temperature is very carefully regulated and followed by means of special electrical recording pyrometers which show the heat at all stages of the burning and the rate of increase in the beginning. The final temperature when the burning is complete is checked by pyrometer cones of the Orton or Seger type.

The method of firing and the perfect control of the temperature are of the utmost importance. If too much heat, the bond is destroyed and the wheel becomes honeycombed or is too hard; if too low a temperature, the wheel is too soft and the bond not properly fused; if the kiln is heated too rapidly the wheels are liable to have hard and soft spots; if cooled too rapidly many of the wheels will be cracked and worthless.

Very small wheels, cylinders, etc., are sometimes burned in muffles of about 1 cubic yard capacity. They do not need so prolonged firing and may be burned and cooled in 4 to 6 days.

Silicon carbide wheels burn grey to grey-black depending on quantity of bond and size of grit.

Regular aluminous wheels are varying shades of dark brown.

Special aluminous, such as No. 38 white "alundum" or "aloxite AA" or those containing almost pure alumina, burn to a brick red.

Natural corundum wheels also burn to a brick red, but slightly darker in colour. They sometimes contain little black spots which are the fused impurities.

ADVANTAGES

The vitrified wheel has a greater range than that made by any other process. Its porosity and great strength of its bond give a high proportion of removed material per cubic inch of wheel wear. Owing to its hardness, the vitrified bond is in itself an abrasive and so assists in the grinding. The wheels are not affected by water, oils, acids, soda, or ordinary temperature conditions and are used for both wet and dry grinding.

Silicate Process

This is a comparatively rapid and easily controlled process. Wheels made with a silicate bond are denser but generally softer than vitrified wheels. They are essentially a cool cutting wheel possessing a comparatively mild grinding action and are used on hardened and tempered steels such as edged tools, cutlery, etc., and for large surface work to prevent the generation of excessive heat. They should not be used for ordinary rough or cylindrical grinding. Solid wheels over 36 inches diameter are made by this process.

When impure natural corundum is used as the abrasive, a better quality of wheel is obtained by this method, as the high temperature of vitrification tends to fuse the impurities and cause black spots.

Until comparatively recently the bonding of silicon carbide by the silicate process was attained with difficulty owing to the smooth surface of the abrasive and to the formation of a thin film of hydrogen gas between it and the alkaline solution. This can be overcome by the addition of an oxidizing agent such as potassium permanganate. The mixing in of a small quantity of fused alumina grain assists in the bonding. In the silicate process the two methods of procedure are known as the "wet" and "dry".

METHODS

Wet Method. This method is used by most manufacturers. The abrasive grain is mixed with liquid sodium silicate; usually zinc oxide is added to render the finished wheel waterproof. The silicate is concentrated to a sticky solution containing about 54 per cent solid. In some wheels no ceramic bonds are used, but the addition of clay or whiting helps to bond as well as dry the mix and thus prevents the danger of the silicate overflowing during the baking period. A filler, such as powdered flint, is sometimes used for special hard wheels; some English manufacturers add a little powdered glass to assist in the bonding. When any of the above materials are used they are mixed in a tumbling barrel with the grain so as to thoroughly coat the latter. The contents are then transferred to a mechanical stirrer where the liquid silicate is added and agitated till the mass is in a semi-dry condition. The sludge is then placed, a little at a time, in a ring mould, the entire surface after each addition being thoroughly pounded by hand with a hammer or wooden bar and the process continued until the mould is filled, when the final hammering is done with a broad-faced mallet. It is claimed that better wheels can be obtained by skilled hand tamping than by any mechanical device, though for certain types of wheels excellent results are obtained by the use of electrical rammers.

For thin wheels, the mixture is rolled in the mould by means of a metal cylinder and, after half the quantity is done, a circular wire web is laid on the surface and the remainder of the mix rolled in. The web is about half the diameter of the wheel and is inserted as a precaution against the wheel breaking at high peripheral speed. Some manufacturers strengthen their thicker wheels with two or even three webs placed at equal intervals and either tamped or rolled.

The silicate wheels, being moulded to exact size, do not require shaving as in the case of the vitrified. After drying for several hours, the green wheels are usually removed from their moulds (though not always) and baked in special electric or coal-fired ovens. The temperature varies according to the type of wheels being made but is between 400° and 550°F., and the time of baking varies from 20 to 80 hours depending mainly on the size of the wheel.

Dry Method. In this method, which is now rarely used on the American continent, the dry powdered sodium silicate is mixed with the abrasive grain, bonds and water being added until it becomes a thoroughly wet mass. This is then placed in a ring mould, a little at a time, and tamped or rolled in a similar manner to that of the wet method until it is well over the surface of the ring. It is then hammered and pounded level by broad-faced bars, thoroughly air-dried, and baked without removing from the mould for about 24 hours at a temperature of not over 300°F. Wire webs are inserted in some wheels as described above.

The wet method is, however, almost universally employed for the following reasons: It is difficult to uniformly mix coarse abrasive grain and fine dry silicate powder and also the silicate is not easily soluble, so that considerable water must be added to obtain a complete solution, resulting in a sloppy mixture which in turn tends to produce an uneven wheel. Also, unless the wheel is carefully seasoned before baking, the steam evolution would be sufficient to rupture the wheel.[1]

On the other hand the bond formed by the liquid silicate is of such a character that the grains break loose after they have become dull from cutting, and thus constantly expose a fresh surface.[2] The wheels so made are not only more uniform than in the dry process, but more controlled variations can be obtained. Some manufacturers obtain greater strength by adding a little powdered silicate to the liquid after mixing.

ADVANTAGES

The silicate method has certain advantages over the vitrified in that the wheels can be made in a few days; are less expensive; the baking process is easier to control; and wheels of any size, even up to 60 inches diameter, can be made. The process can be used by the small manufacturer as it requires comparatively little plant or machinery.

Elastic or Shellac Process

These wheels, as the process implies, will yield slightly to strain. They are less porous than the vitrified wheels and will not stand much heat. This process is mainly used for the manufacture of very thin wheels for light grinding operation, such as delicate cup and dish wheels and other thin forms used for cutting off, slotting, fine saw gumming, cutter and reamer sharpening, for producing a high finish on ball races, etc., and for the grinding of granite and marble. Since the grain used is always fine, they are also sometimes used for high finish work, such as for steel rolls, and hardened steel cans. In some instances they are used for grinding aluminium pistons.

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[1] Vail, J. G.: "Soluble Silicates in Industry". Am. Chem. Soc., Monograph No. 46, 1928.

[2] Private information, Philadelphia Quartz Company.

A detailed description of the process of manufacture follows:—

The bond consisting of flake or powdered shellac is mixed with the grain in a steam-heated mixing machine until the melted shellac has thoroughly coated each grain. The mass is then laid out to harden and then put through rolls set wide enough apart to break up the mass into small aggregates, but not to fracture the abrasive grain, after which any oversized lumps are screened out.

For the manufacture of thin wheels of $\frac{1}{8}$ inch or less, the screened aggregate is placed in a mould the exact size of the wheel, fitted with a false bottom which can be heated to make the mass plastic. The mixture is then rolled to the exact thickness with a steel roller and a hot lid is placed on top and clamped down tight. When stiff, the wheel is removed from the mould, placed in sand and baked in an oven for about 12 hours at 300°F.

For thicker wheels the aggregate is tamped into hot, heavy steel moulds, a lid inserted and subjected to hydraulic pressure (Plate XB). After setting, the wheel is removed and baked in the oven for about 24 hours at 350° to 400°F.

Instead of shellac, some English manufacturers use boiled linseed oil to which varnish resin or gum has been added so as to produce a sufficiently viscous mixture.[1] This is treated and baked at 250°F. as described above, allowed to cool for a short period, and then re-baked at a temperature of about 350°F. for 12 hours. Occasionally linseed oil or creosote is used as a bond in combination with the shellac.

Shellac wheels over $\frac{1}{8}$ inch thick must be trued with a diamond after baking.

ADVANTAGES

Shellac bond wheels are quite elastic and will withstand severe centrifugal strains and considerable side pressure. They can be used either wet or dry. Very thin wheels of $\frac{1}{32}$ inch thickness can be made, which are of sufficient strength to be used in safety. For some classes of work a finer finish can be imparted with a shellac wheel than by any other type. The process of manufacture is rapid and easily controlled.

Bakelite Process

Synthetic resins such as "Bakelite" or "Redmanol" are rapidly replacing shellac wheels. Their range of uses is larger than the shellac, though the finish obtained is not quite so good and in this respect they resemble the vitrified wheel. Bakelite bonded wheels were originally adopted for precision work and for the manufacture of thin wheels for cutting off, saw gumming, etc., for which they are in many cases superior to the shellac. Recent developments have shown that the coarse types of Bakelite wheels are invaluable for general rough work necessary for snagging castings and for which in some instances they have replaced the vitrified wheels.

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[1] Searle, A. B.: "Abrasive Materials"; Pub. by Sir Isaac Pitman & Sons, London, p. 49 (1922).

The finely powdered Bakelite is mixed dry with the grain and a small quantity of special solution is added to make it just plastic. After thoroughly mixing, the mass is forced through a sieve to separate the Bakelite-coated grain into small aggregates. These are placed in heated steel moulds of the required size and are rolled by means of a steel roller. Thicker and denser wheels are made by subjecting the mixture to hydraulic pressure in a steam or electrically heated press. For the more open type of wheels the mix must be cold and the blanks regardless of their thickness are pressed hydraulically in a cold press; best results are obtained during the winter months. The wheels are then baked in an oven to about 300°F. between iron plates, to preserve their shape.

ADVANTAGES

The outstanding advantages of these wheels are that they can be operated at higher speeds (9,000 p.f.p.m.) than vitrified wheels (5,000 to 6,000 p.f.p.m.) and their rate of cutting is very rapid, consequently they have lowered snagging costs and have increased production. Other advantages are their general range of application and the fact that they are unaffected by the ordinary heats generated in grinding and consequently have less tendency to burnish the work. Wheels of comparatively hard grade can also be produced. The supply and quality of Bakelite are uniform, whereas the quality of shellac, which is an organic material, is not always uniform and being imported from the tropics, the supply is not always regular.

Rubber Process

Rubber bond or vulcanized wheels will function only when the rubber is melted. They must, therefore, be operated at a high enough peripheral speed—about 8,000 to 10,000 p.f.p.m.—to melt the bond by friction against the work, otherwise they will glaze and will not cut. The large wheels should be mounted on heavy standards to absorb the abnormal vibration, protected by safety guards, and run at a constant speed. The wheels are improved by age and should be kept 2 to 3 months after being made before using.

Although natural emery is now seldom used as the abrasive, the best Turkish emery, on account of its certain degree of toughness, is claimed to be particularly suitable for wheels which are used to give a high finish or polish.[1]

Vulcanized wheels are used in the form of very hard, thin wheels employed for purposes similar to those of the shellac bonded wheel. Large coarse wheels, of 24 inches in diameter and 2 to 3 inches thick, are also largely used for snagging heavy steel and malleable casting.

The rubber bond wheel has a wide use as the "feed" wheel in centreless grinders, but in this case there is of course no grinding action. On account of its great hardness it holds its shape better and lasts longer than other types of wheels. The manufacturing process is as follows:—

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[1] Private information. New York Belting and Packing Co.

Weighed amounts of the best crude rubber sheeting, abrasive grain, flour sulphur (as the vulcanizing agent), and some rouge are mixed by passing between rolls. The sheet is folded on itself and passed through a great many times while the grain is gradually spread on until it is considered to be thoroughly and uniformly mixed. Steam-heated rolls are sometimes used but the rolls usually become heated by the friction which assists in the process, but if they become too hot the rubber melts and sticks. Some manufacturers first pass the composition through rolls in a vertical downward direction and when uniformly mixed again pass horizontally through a calender roll set to the desired thickness. The rubber sheet is then either cut to the exact size by circular ring dies (dieing-out machine) or by a sharp knife and the centre hole punched, after which it is pressed in hot moulds and left to vulcanize. The rubber should not be rolled to more than 1¼ inches in thickness. Thick wheels are made up in a series of sheets and pressed and vulcanized together.

Some wheels are moulded on special iron centres which can be constantly refilled. They can be safely operated at high speeds and the wasteful discarding of stubs is eliminated.

Wheels of over ⅛ inch thick have to be trued with a diamond.

Some European manufacturers make a solution by dissolving the rubber in hot oil or other solvent. When the solution is cooled, the abrasive and sulphur are added and thoroughly agitated in a steam-heated mixer until a stiff paste is formed. This is then moulded while still warm and subjected to a hydraulic pressure of 2,500 to 3,000 pounds per square inch for several minutes and then vulcanized. For small wheels the paste is passed between rolls and the forms cut out from the resulting sheet and treated in the usual manner.

ADVANTAGES

Although the uses of vulcanized wheels are limited, their main advantages are their great hardness (being considerably harder than shellac), durability, and comparative safety when subjected to severe strain.

Finishing of Wheels

The unfinished wheels made by any of the processes already described have to go through a series of operations before they are ready for use. Brief details of these operations are as follows:—

Sorting. The wheels are first examined for cracks and tested for soundness by striking or "ringing", any defective wheels being discarded. All that have passed are sorted by size and into grit and grade by examining the special marks stamped on the green wheels before heat treatment.

Truing. After sorting, the wheels are delivered to the truing room. Here they are mounted on lathes—gripped in a universal chuck and trued all over each side and face and to the exact dimensions, great care being taken to preserve the balance. Conical hardened steel cutters are generally used which are clamped at an angle against the portion of the revolving wheel that is being trued. The cutter rotates by the pressure against the grinding wheel. For the face of small wheels the ordinary type of star-tooth dresser is used, while for thin and for some types (particularly elastic or rubber) of wheels a diamond pointed instrument is employed.

It is also necessary to true and dress wheels to keep them in perfect shape and condition during their period of operation.

Bushing. The wheel is held flat on a special fixture or adjustable "bushing clamp" which locates it centrally, and a mandrel or "arbor" of the correct size is inserted in the centre of the spindle hole and the space between is filled all round with molten lead. The lead is poured through "cleaners" which cover the wheel and keep the lead from flowing over the wheel face. The bushed hole is made very slightly larger than the diameter of the spindle upon which the wheel is to be mounted, for if the hole be too small the wheel might be broken by undue forcing, but if too large, the wheel may not run true or be out of balance. The limits of excess lie between 0·002 and 0·005 inch in diameter. After the arbor has been removed the bushing is trimmed flush with the side of the wheel by means of a chisel. This precaution is necessary so that there will be no lead protruding to interfere with the even bearing of the wheel mount flange. If the grading has already been done, the grade, grit, and bond symbols are stamped on the soft bushing, thus leaving a permanent and useful identification.

Although lead is generally used, Babbitt, being somewhat harder, is used for heavy duty wheels.

Balancing. Owing to the high speeds at which a grinding wheel is operated, its accurate balance is a very important item. Surface defects developed after use are largely caused by improperly balanced wheels, though this out-of-balance may in some cases be due to improper mounting. Perfect balance is essential for the accurate work required for precision grinding.

The balance of an unused wheel is affected by the position of the spindle hole, slight unevenness of the density of the material in the wheel, or thickness variations due to the truing operations. Counterbalancing is effected in the following ways:—

A special arbor (with bushing if necessary) is inserted in all wheels of over 12-inch diameter and the arbor ends are placed on a raised frame with two parallel horizontal straight edges called the "balancing ways". The wheel is then revolved and when it comes to rest the top or light point is marked and the operation repeated several times to check. Sufficient weights are then attached to the periphery at this point by means of spring clips, so that the wheel remains steady when rolled at 90 degrees in either direction. The total weight of the clips and weights is recorded on the wheel and later a calculated amount of material is chipped out from the light side near the spindle hole and replaced by enough lead to produce a true balance. Special balancing wheel sleeves and flanges are made by the larger wheel manufacturers both for their own use and for sales distribution. This flange is provided with a dovetail groove in which there are two sliding balancing weights that are adjustable about the groove.[1] The method of testing is the same as described and if the two weights are touching at the top it shows a maximum out-of-balance, and when opposite each other in a straight line with the centre no counter-balancing is necessary. The amount of lead to be added is calculated from the angle between the centre of the two weights with the centre of the spindle, the smaller the angle the greater the amount of lead required.

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[1] Norton Company. Trade literature.

Wheels having large holes (over 5 inches) are mounted on spiders.

Speed Testing. All wheels of over 6 inches diameter are given a speed test of at least 50 per cent greater speed than that at which they are recommended to be run normally. The centrifugal force is proportional to the square of the speed, so that during the test the stress exerted is double that of the normally operated wheel.

The wheels are mounted on a heavy stand equipped with variable-speed counter shafts to which an accurate speed gauge is attached. The machine is enclosed in a stout steel or oak-bound protection box which retains the fragments in case the wheel bursts. A careful record is kept of the speed at which each wheel has been tested and is entered on the wheel tab as well as in a book. At the end of the day the men who do the work usually have to swear before a notary public as to the correctness of their test data. A wheel after passing this test is considered absolutely sound and the danger of breaking when used under the proper and recommended conditions, is practically nil. Accidents due to breaking have almost in every case been traced to other causes than that of a faulty wheel, particularly to improper mounting.

On account of the relatively light weight of silicon carbide, wheels made of this abrasive will generally (all other conditions being equal) withstand slightly greater speeds than with any other.

Final Grading. Although some manufacturers use mechanical methods for grading, the majority still resort to hand grading. The tool used resembles a thin-edged screw-driver with a stout handle. The operator presses the tool into the side of the wheel at several places and at the same time gives the tool a slight twist. The sound so produced and the resistance offered to the twisting motion indicate the grade of the wheel which is determined by a comparison with certain standard wheels of known grade and is then recorded on the wheel certificate. This method requires very considerable skill and experience on the part of the operator, but his hearing and sense of touch become very reliable. However, until an accurate universal grading machine is invented, accurate standardization of the grades of wheels made by all manufacturers can never be accomplished—an accomplishment which is badly needed.[1] There are about 25 degrees of hardness, the grade symbols for which are described later.

Labelling and Inspection. A circular label is usually pasted on the sides of the wheel upon which is printed the firm's name, wheel trade name (thereby indicating silicon carbide or fused alumina), and other data. Each wheel is also provided with a tag, or certificate giving full details such as grade, grit, process of manufacture (Vit., Sil., Shel., Bak., or Rub.), diameter, thickness, size of hole, shape of wheel, speed at which tested, operating speed limits, order number, etc.

The finished wheels are then inspected carefully to check any errors in the certificate, or search for flaws, after which they are sent either to the wheel storage room, or packed for shipment. Plate XA shows a general view of a wheel grading and inspection department.

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[1] A mechanical grading machine for testing the hardness of grinding wheels has recently been put on the market by the Abrasive Engineering Corporation, Detroit. For details see "Abrasive Industry", May 1929, p. 43.

Wheel Designation

Each wheel as it leaves the factory is stamped with its grade, grit, and other details.

Grit

The manufacture and final production of the many sizes or grades of abrasive grain (20 sizes from 8 to 220) have already been described. The number refers to the size of the particle or mesh; thus a 40 is regarded as a grain that will just pass through a screen having 40 meshes per lineal inch or 1,600 meshes per square inch. If several grits are incorporated in the wheel, such as 40, 60, and 80, it is termed a "40-combination" by some manufacturers, the coarsest being the one indicated (Norton Company). In some cases the coarsest grit is followed by the number of the combinations, thus the above would be represented by "403" (Carborundum Company). A "mixed" grit is one in which two or more abrasives are used, thus "mixed 403" signifies a wheel made of a mixture of silicon carbide and fused alumina of 40 and two other grits.

The grits in greatest demand are the medium or numbers 30, 36, and 46.

Combination grits are particularly suitable where both fast cutting and smooth finish are required such as cylindrical grinding.

Grade

The "grade" of a grinding wheel denotes its relative or degree of hardness and represents a measure of the strength of the wheel bond or the cohesive force exercised by the bond to retain the grit in its setting, Thus a *hard* wheel is one in which it takes a considerable force to dislodge the grit and in a *soft* wheel the grain breaks out comparatively easily. A grade is not an exact value but a range between limits. This should not be confused with "grain grade" which denotes size or mesh of grain and is not a measure of its hardness or purity. There are approximately 25 grades of wheels made and each grade is usually symbolized by a letter of the alphabet. Unfortunately, however, this letter is not standardized, but most manufacturers indicate the extremely soft (vitrified or silicate wheels) as E to G, the medium M, and the extremely hard U to Z, the other grades coming in between. Also a "G" soft wheel by one firm may be the same hardness as "H" soft wheel made by another. The Carborundum Company's grading is reversed, while M is still medium, D is very hard, and Z is very soft. M represents a tensile strength of about 1,925 pounds per square inch. For the softer grades, each grade letter represents a difference of approximately 100 pounds per square inch and for the harder than M the difference is somewhat less.

The physical properties and methods of testing abrasive wheels are detailed by Purdy and MacGee.[1]

A grading chart of some of the principal manufacturers is given below, from which comparisons can be made and the other symbols for the shellac or rubber wheels will be noted.

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[1] Purdy, R. C. and MacGee, A. E.: "Some Physical Properties of Artificial Abrasives"; Jour. Am. Ceram. Soc., vol. II, No. 3, pp. 192–203 (March 1928).

TABLE IV

Wheel Grade Symbols of Various Manufacturers Compared

Name of grinding wheel manufacturer..........	Carborundum	Vitrified and Silicate											Carborundum Elastic	Norton Elastic, Bakelite, Rubber*	Abrasive Elastic	American Silicate	American Elastic	Detroit Elastic
		Norton	Abrasive	American	Safety	Sterling	Chicago	Vitrified	Courtland	Star	Hampden	Detroit						
											Z							
		Z									Y							
		Y									X							
		X									W							
		W		Z				G			V	Z+4						
Very hard............		V	Z	W							U	Z+3						
		U	W	V		6		F3			T	Z+2						
		T	U	U							S	Z+1						
	D	S	T	T	D	5¾		F2			R	Z						
					E¾													
				S	E½	5½						Y				7		
					E¼													
	E	R	S	R	E	5¼			R		Q	X				6		
	F		R		N¾	5		F1		Z								
						4¾						W					7E	
					N½	4½				Y								
						4¼												
	G+	Q	Q+	Q	N¾	4	F		Q	G1	P	V	1	7	7E	5		7
	G		Q		N	3¾				G		U						
Hard..................										F2	O							
	H+		P+		O¾	3½	E1				N	T		6	6E		6E	6
	H	P		P	O½		E	F	P	F1	M	S	2			4½		
					O¼													
	I+		P		O	3¼	D3	E3		F	L	R			5E		5E	
					1¾			E2						5				5
					1½												4½E	
					1¼			E1		D2					4E			
	I	O	O+	O	1	3	D2	E	O		K	Q		4		4	4E	4
					P¾					D1								
					P½			D3			I							
					P¼	2¾	D	D2		D			3		3E			
	J	N	O	N	P				N		I	P		3		3¼	3½E	3
Medium................								D1		C2								
	K	M	N	M	M¾	2½		D	M	C	H	O	4		2½E	3	3E	
					M½		C1	C3										
								C2			G			2½	2E			2½
	L	L	M+	L	M¼	2¼		C1	L	B2	F	N				2½	2½E	
	M	K	M	K	M	2	C	C	K	B1	E	M	5		1¾E	2		
	N		L+		A¾	1¾	B2					L	6	2	1½E		2E	2
					A½													
	O	J		J	A¼	1½	B1		J	B		K				1½	1½E	
Soft...................	P		L	I	A	1¼	B			2H		J			1¾E	1	1E	
	Q		K+		H½							I		1½				1½
	R	I			H	1	A1	B				H	7		1E			
	S		K		C½		A			W		G	8		¾E			
	T	H	J	H	C							F	9			¾	¾E	
	U	G	I	G								E	10	1	½E	½	½E	1
	V		H									D						
Very soft.............	W	F										C	11		¼E			
	X		G									B						
	Y											A						
	Z	E																

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*Rubber has the letter R in front of numeral.

[1] Reproduced from pamphlet on "Gradings" issued by the Carborundum Company.

It will thus be seen that the true grade of any of the manufacturers cannot be compared by the similarity of their symbols, and standardization is urgently needed.

Type Symbols. The grit and grade, and special type of abrasive (when used), are stamped on the wheel using the above combination of symbols. For example, a wheel marked or listed as 3860 M or 6648 C-J denotes No. 38 or No. 66 special aluminous abrasive (Norton's) with a 60 grit or 48 combination grit and grade, a hardness of M (medium) or J (soft). A single set of numerals—60 P denotes the regular of 60 grit and P (medium hard) grade. The name of the manufacturer must, however, be known in order to correctly read the designation since each have different methods. The abrasive itself is indicated by the trade name.

Grinding Wheel Manufacturers

Approximately 75 per cent of the grinding wheels throughout the world are supplied by about 50 concerns in the United States and in Canada.

The Canadian concerns and trade names of their wheels are given in Table V.

TABLE V

Trade Names of Canadian Grinding Wheel Manufacturers

Name of manufacturer	Address	Aluminium oxide	Silicon carbide
Brantford Grinding Wheel Co.	Brantford	Alobrant	Carbobrant
Canadian Carborundum Co.	Niagara Falls	Aloxite	Carborundum
Canadian Hart Wheels	Galt	Rexite	Cresolite
Dominion Abrasive Wheel Co.	Mimico	Excelite	Carbolox
Lion Grinding Wheel Co.	Brockville	Alulion	Carbolion
The Norton Co.	Hamilton	Alundum	Crystolon
Ontario Abrasive Wheel Co.	Prescott	Alunox	Carbo

The value of the output for the last four years, from the above concerns is as follows:—

TABLE VI

Canadian Production of Grinding Wheels Giving Value of Wheels and Materials Used

Year		1925	1926	1927	1928
Value	$	401,294	626,124	602,895	858,323
Abrasive grain	Tons	530	649	683	816
Total clay bonds	Tons	230	221	213	319

The Selection of Grinding Wheels

The proper selection of the best type of grinding wheel for each class of work is highly necessary and the importance of this is greatly stressed by the wheel manufacturers. To accomplish the best results many factors regarding the type of work and working condition must be considered.

Special booklets are issued by the leading wheel manufacturers giving the types and grades of wheels recommended for the numerous grinding operations. Some of these lists detail as many as 450 different types of work and operation and give the most suitable wheel for each.

There are three general factors governing wheel selection which may be summarized as follows:—

1. The characteristics of the wheels as determined by its manufacture.
2. The nature of the material to be ground.
3. Factors having to do with methods and conditions.

A general tabulated form prepared by the Norton Company is hereby reproduced. A careful study of this table will reveal a considerable amount of accumulated and interesting information concerning the factors which influence grinding operations.

TABLE VII

Tabulation of Selection Factors for Grinding Wheels[1]

FACTORS AFFECTING THE SELECTION OF THE ABRASIVE

Physical properties of the material to be ground	Use Alundum (fused alumina) grinding wheels for materials of high tensile strength	Carbon steels Alloy steels High speed steels Annealed malleable iron Wrought iron Tough bronzes Tungsten, etc.
	Use Crystolon (silicon carbide) grinding wheels for materials of low tensile strength	Grey iron Chilled iron Brass and bronze Aluminium and copper Marble Granite Pearl Rubber Leather, etc.

FACTORS AFFECTING THE SELECTION OF THE GRIT

A. *Amount of material to be removed*	Use coarse wheels for fast removal of stock
B. *Finish desired*	Use fine grain for fine finish
C. *Physical properties of material to be ground*	Use coarse grain for ductile materials and finer grain for hard, dense, or brittle materials

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[1] Norton Company: "Grinding", pp. 69-71 (1926).

TABLE VII—*Concluded*

Tabulation of Selection Factors for Grinding Wheels—Concluded

FACTORS AFFECTING THE SELECTION OF THE GRADE

(Degree of Hardness)

A. *Physical properties of the material to be ground*	Use hard wheels on soft materials and vice versa
B. *Arc of contact*	The shorter the contact, the harder the wheel should be
C. *Wheel speed and work speed*	The higher the ratio of work speed to wheel speed the harder the grade should be and vice versa
D. *Condition of grinding machine*	Machines in poor condition require harder wheels than machines in good condition
E. *Skill of operator*	Skilful operator can use softer wheels than unskilled man—softer wheels mean more economical production Piece-work grinding usually calls for harder wheels than day work

FACTORS AFFECTING THE SELECTION OF THE PROCESS

A. *Dimensions of wheel*	Wheels subjected to bending strains should be made by elastic or rubber process Extremely thin abrasive saws must be made by the elastic or rubber process Wheels over 36-inch diameter are usually made by the silicate process
B. *Rate of cutting*	Use vitrified wheels for most rapid cutting at speeds under 6,500 s.f.p.m.; rubber wheels at higher speed
C. *Finish desired*	Use elastic or rubber wheels for highest finish, where rapid production is not a factor Use silicate wheels to replace sandstones on cutlery, etc.

A further explanation of some of these items is as follows:—

The Abrasive

Fused alumina is used for materials of high tensile strength, and silicon carbide, for those of low. This is due to the fact that the grains of the alumina, while not so hard, are tougher and do not fracture so easily, and thus are able to withstand a greater stress than the silicon carbide. The former have also a greater range of toughness due to their degree of purity and variation in crystal size.

Natural abrasives are now very rarely used on account of the irregularity of their supply, the uncontrolled variations of purity and inconsistency of their abrasive temper. Emery wheels are occasionally used in some snagging operations which do not require too harsh a grit. One firm still specializes in rubber bond emery wheels where very high finish or polish is required. Turkish emery is superior to the Naxos (Greece) for grinding wheels; the American is much too low grade. The highest grade corundum is still regarded by some as being superior to the artificial for certain classes of tool-cutting and precision work, for which the Canadian product was entirely suited,[1] but supplies from this source are not at present available.

Although the dividing line between a material of low and high tensile strength cannot be definitely fixed, a strength of 50,000 pounds per square inch may be considered, below and above which one of these two types of abrasive should in most cases be used.

The Grit. The coarse grain, such as used for rough snagging of castings, may run from 8 to 24; Nos. 24 to 60 being usually employed for heavy tool grinding, cylindrical grinding, and general precision work. For a fine finish and for fine-edged tools Nos. 60 to 100 or finer are preferred.

Nature of Material to be Ground

Grade. The reason for the use of hard wheels on soft material and vice versa is that with hard material the bond should be soft enough to allow the grain to be torn out or broken off fast enough to keep fresh grains continually cutting. With a softer material the grain does not dull so quickly and thus should be retained longer in the bond—a hard wheel. Ductile materials, as Babbitt, copper, etc., are, however, exceptions, since the abraded particles load a hard wheel.

Arc of Contact. The arc of contact is the length of the arc that is in contact with the work. The extremes being a very large wheel grinding a small round piece of work and a wheel continually grinding a hole slightly larger than the wheel itself. In the case of cup or cylinder wheels where the grinding is done on the rim, the arc becomes the "area" of contact and varies from the grinding of steel balls to the grinding of broad, flat surfaces. The larger the arc or area, the softer should be the grinding wheel. The "width of contact" is the width of the wheel in contact with the work and has practically no effect on the cutting action of the wheel.

Wheel Speeds. The peripheral or surface speed should be in accordance with the recommendation of the maker. This is discussed in more detail later.

Work Speed. Usually fast work speed tends to wear out the wheel faster than a slower work speed. Wheel wear is dependent on the ratio of the wheel speed to the work speed—low ratio causes heavy wear. The greater the arc of contact the greater should be the speed of work.

The Process. The processes by which wheels are made and their principal applications have already been described when detailing their manufacture.

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[1] For further information on Corundum and Emery, *see* Part II.

Shapes of Wheels

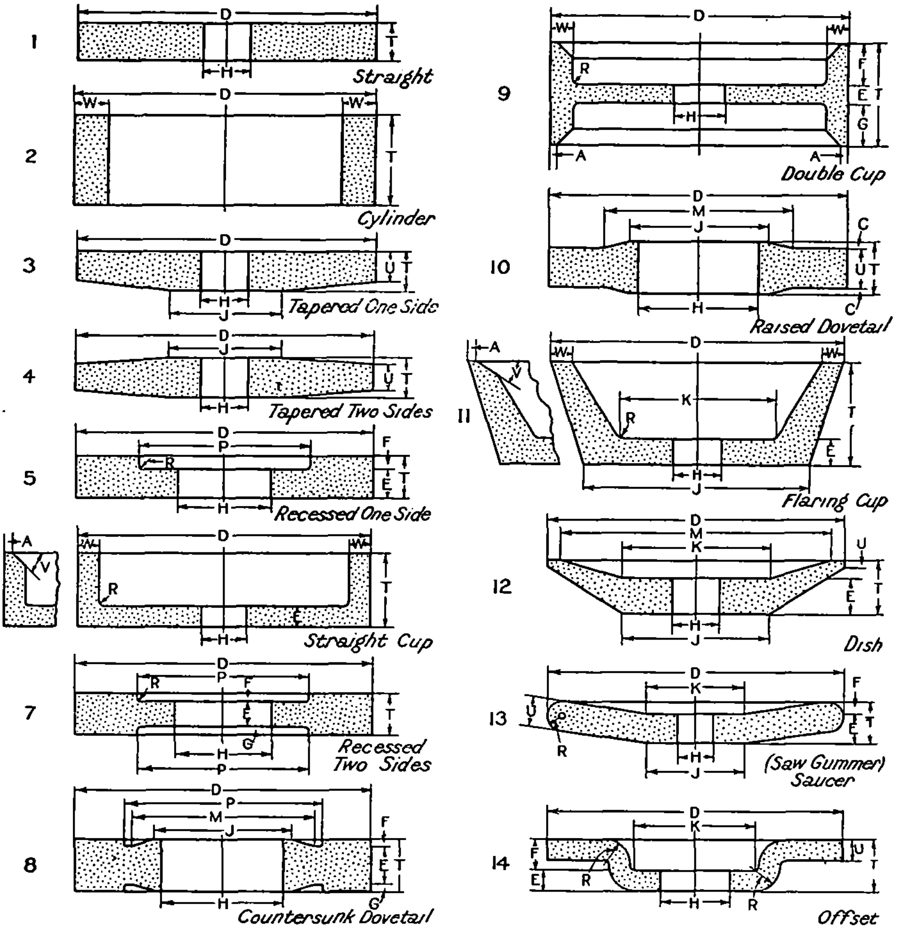
Until quite recently there were about 725,000 different sized and shaped wheels in use—every user giving special orders for almost every type of grinding. The numbers were used to such an extent that the Grinding Wheel Manufacturers' Association in co-operation with the principal manufacturers brought out a partial standardization thereby reducing the number of wheel sizes and shapes by about 260,000. These are now represented by 14 standard types which are shown in Figure 9. Any one or more of these types can be used for the great majority of grinding purposes, the dimensions of which are variable according to the work and the preference of the user.

In the diagram, Figure 9, Nos. 1 and 5 are standards for internal cylinder and cylindrical grinding. In the first-named, for example, D is $\frac{1}{4}$ to $2\frac{1}{2}$ inches and T $\frac{1}{4}$ to $1\frac{1}{4}$ inches; for cylinder grinding D is $2\frac{1}{2}$ to $4\frac{1}{2}$ inches and T $\frac{3}{4}$ to $1\frac{1}{4}$, while for cylindrical grinding, which calls for larger wheels, D is 10 to 26 inches and T as ordered, the hole H being 5 to 12 inches. The diameters of standard cylinder wheels (No. 2) vary from 8 to 30 inches with a wall of 1 to 3 inches thick, and for standard dish and flaring cup wheels the diameters may be from 3 to 8 inches. The diameters of straight cup for general use are 8 to 30 inches and T 4 to 6 inches, but for tool room grinding they are smaller, being 2 to 5 inches in diameter and $1\frac{1}{2}$ inches thick.

Special Types of Wheels

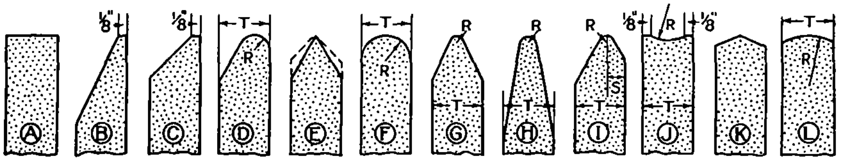
There are a large variety of shapes of grinding wheels not included in the standard forms such as the wheels specially made for the numerous makes of grinding machines as well as odd shapes such as cone wheels, pot balls, skillet wheels, etc. There are a great many forms of cylinder wheels used for vertical surface grinding in which the wheel rotates horizontally with a vertical spindle, the grinding being performed by the side or rim of the cylinder. Some of these wheels are reinforced on the outside with wire or thin hoop iron rings and are largely used with the Blanchard or other similar makes of surface grinding machines. The thin cutting-off wheels of recent design are made with a "clearance" or reversed taper so that they are very slightly wider at their periphery and taper towards their centres. This eliminates side grinding and binding, and consequently saves power.

Segmental Wheels. The use of the large sized wheels made in segments is increasing. The main advantages are that worn or broken segments can be replaced comparatively easily and cheaply and the grindings can collect or pass away between the segments and thus keep the wheel free, also very large wheels are now made in segments which it would be impossible to produce in the form of a solid wheel. Some of these wheels are 6 feet in diameter (Plate XI) and are now being employed to replace the large natural grindstones, particularly in England. The segments are generally bonded together by the wheel manufacturer but in some instances can be done by the users. In one of the latest types, special chucks are made to take segments which are fixed at intervals round the chuck by means of wedge-shaped bolts. These are being used as cylinder wheels with the Blanchard and other types of vertical surfacers.



STANDARD TYPES OF GRINDING WHEELS

A-Flat Spot of Bevelled Wall. C-Height of Dovetail. D-Diameter (Over All).
E-Centre or Back Thickness. F-Depth of Recess (See Type 5) G-Depth of Recess (See Types 5 and 7)
H-Arbor Hole. J-Diameter of Flat or Small Diameter. K-Diameter of Flat Inside
M-Large Diameter of Bevel. N-Small Diameter of Bevel. P-Diameter of Recess.
R-Radius. T-Thickness (Over All). U-Width of Face. V-Angle of Bevel. W-Thickness of Wall



STANDARD SHAPES OF GRINDING WHEEL FACES

Figure 9. Standard types of grinding wheels approved by Grinding Wheel Manufacturers' Association of the United States and Canada.

Artificial Pulpstones. For many years attempts have been made to produce wheels to replace the unreliable natural pulpstone, descriptions and uses of which are briefly detailed in Part I of this series.[1] A slight measure of success appears to have been achieved by Norwegian and German inventors, but their products are not so satisfactory as the segmental wheel recently produced by the Norton Company. The Norton stone is shown in Plate XII which clearly indicates the detail of the wheel construction. They are made in different sizes but mainly the 62-inch magazine type. The segments are silicon carbide with a vitrified bond, the abrasive being specially selected for the purpose. One of the greatest difficulties was in obtaining a suitable cement to be used between the segments. A special alloy has now been selected for its physical properties, which not only permit it to wear away at the same rate as the blocks, but also cause it to expand so as to maintain a continuous bond between the blocks and the cast-iron centre as the latter expands and contracts under the temperature changes. This alloy is poured into the spaces between the segments after they are securely bolted in place.

Although the initial cost of this artificial stone is higher than that of the natural pulpstone, this cost is offset by a considerably longer life (3 to 5 years), far less dressing or burring required, no seasoning, and a constant and uniform supply. The quality of the pulp made is stated to be high. This stone has only been in use a comparatively short time but the demand is increasing.

Mounting of Grinding Wheels

Although accidents are now comparatively rare, the most are probably due to improper mounting, so that the greatest care must be taken to ensure a correct mount. A grinding wheel, after satisfactory inspection (to ensure against any damage in transit), is mounted rigid and supported so that it revolves true with respect to the plane of the wheel and cutting face. It must fit freely but not too loosely on the spindle (hole 0·005 inch larger than the spindle's diameter). All wheels should be mounted on flanges; the sides of the wheel must be absolutely level with no protruding bushing or foreign particles that might interfere with the even bearing of the flanges. These flanges should be recessed at the centre so that they may bear on the outer edges only, and a full size compressible washer should be placed between the wheel sides and the flanges in order to distribute the pressure and take up any imperfections. The two flanges must be of the same diameter which should be at least one-third that of the wheel for straight wheels and at least two-thirds for tapered wheels, particularly where no hood is used. Spindle nuts should be tightened only just enough to hold the wheel firmly.

Wheels running over 2,000 s.f.p.m. should, whenever practical, be provided with a hood or some form of protection device and protruding spindle ends and nuts should be guarded.

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[1] Ab Part I—Siliceous Abrasives," Mines Branch, Dept. of Mines, Canada, Rept. No. 673, pp. 35-44.

Mounting Cylinder Wheels

This type of wheel (No. 2, Figure 9) is now usually first mounted on an iron back. The advantages over the plain unmounted wheel are that they are safer and are preferable to some cup wheels; in larger sizes the price per wheel is less and the wheel can be used down to a smaller size before discarding. There are several cementing mediums of which sulphur is the commonest. The wheel should be carefully warmed to about 120°F. and the hot sulphur is then poured onto the back into the space between it and the wheel. The wheels can be used as soon as the back is cool. The stubs can be easily removed. Table VIII gives some of the cementing mediums and their characteristics.[1]

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[1] Norton Company: "Grits and Grinds"; April 1928, p. 11.

TABLE VIII

Characteristics of Cementing Materials for Cylinder Wheels

Material	Safe operating temperature	Comparative strength A=Strongest B=Medium C=Weakest	Method of applying	Setting time	Effect of common lubricants	Remarks
Sulphur	220°F.	C	Pour hot	Until cool	None	Fairly wide joint necessary to facilitate pouring.
Lavasul (Sulphur and coke compound)	220°F.	B	Pour hot	Until cool	None	Fairly wide joint necessary to facilitate pouring.
Shellac	200°F.	C	Fill recess and press wheel in place.	Until cool	Weakened by alkaline solutions.	Very thick when hot. Will not flow readily.
Trinidad asphalt	200°F.	B	Pour hot or fill recess and press in place.	Until cool	Some oils may affect this.	Slightly flexible even when set. Softens easily.
Magnesium oxychloride (Calcined magnesite and fused magnesium chloride).	380°F.	A	Spread cold over surfaces.	15 hours at room temperature.	Slightly affected by water.	Ingredients must be properly prepared and stored.
Sodium silicate	380°F.	A	Spread cold over surfaces.	12 hours at 212°F.	Soluble in water, must be used dry.	Will not bond with treated wheels.
Litharge-glycerine (Litharge and C. P. white glycerine).	380°F.	A	Spread cold over surfaces.	12 hours at room temperature.	None	Litharge is poisonous. Also difficult to remove stubs from backs.

The lubricants referred to in the above table are discussed later.

Weights of Grinding Wheels

Before mounting a large wheel it is useful to know its weight. Tables are provided by the principal wheel manufacturers but an approximation can be obtained from the following formula for carbide wheels, in pounds:

$$\text{Vitrified} = \frac{d^2 \text{ x } t}{15}; \quad \text{Silicate} = \frac{d^2 \text{ x } t}{13},$$

where d = diameter and t = thickness of wheel in inches.

Silicon carbide vitrified wheels are the lightest, the elastic being 20 per cent, the vitrified aluminous 7 per cent, and silicate and elastic alumimous, 30 per cent heavier. A 36-inch by 4-inch elastic aluminous wheel weighs nearly 500 pounds.

Grinding Wheel Operating Speeds

Proper cutting action and best all-round results can be achieved only by running the wheel at the proper speed, no matter how well suited the wheel may be for the work. The speed depends largely on the kind of wheel used, nature of the work, and type of grinding machine employed. As a result of long practice and many experiments, the leading wheel makers have determined certain speed limits for various types of grinding and for the different processes by which the wheels are made.

The general average speed in peripheral or surface feet per minute (s.f.p.m.) is about 5,000. At this speed the stress on the wheel is about 90 pounds per square inch, while at say 9,000 it is as much as 250 pounds, hence the necessity of not exceeding the speeds recommended by the wheel makers. The following table showing some typical working speeds is hereby given.

TABLE IX

Grinding Wheel Operating Speeds[1]

—	Peripheral or surface speed, in feet per minute (s.f.p.m.)	
	Standard	Maximum
Type of Grinding—		
Cylindrical grinding	5,500	6,500
Internal grinding	5,000	6,000
Snagging and general off-hand grinding on bench and floor stands	5,000	6,000
Surface grinding	4,000	5,000
Knife grinding	3,500	4,000
Hemming cylinders	2,100	2,400
Wet tool grinding	5,000	6,000
Cutlery grinding	4,000	5,000
Vitrified and Silicate Wheels—		
Cup and cylinder wheels when used for rough grinding on bench, floor, portable machines, etc	4,500	5,500
All other vitrified and silicate bonded wheels	5,000	6,500
Rubber and Shellac Bonded Wheels—		
Rubber, shellac, and Bakelite cutting-off wheels	9,000	12,000
All other shellac bonded wheels	5,000	6,500

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[1] Data from Norton Co., Carborundum Co., and F. B. Jacobs.

In order to find the revolutions of the wheel per minute necessary to obtain any one of the above speeds, divide the surface speed by the wheel circumference in feet, or multiply surface speed by 12 and divide by 3·14 times the wheel diameter in inches.

The average speed for general utility wheels is about 5,000 s.f.p.m. For "wet" grinding, wheels should be run 20 per cent slower than for dry grinding because of greater strain due to added weight of wheel. Wheels with an unusually large hole such as cup or cylinder wheels are weaker than solid wheels and should be run 15 to 20 per cent slower as indicated in the table.

However, other factors have to be considered when the work itself is either revolving or reciprocating, such as in precision grinding. The speed of the wheel is to some extent governed by the arc of contact (see previous explanation) since the greater the arc the softer the wheel used and the slower the speed it should revolve to prevent the wheel from burning. In surface grinding for example, the arc of contact is considerably greater than is the case of cylindrical work.

Speed and Apparent Grade

By increasing or decreasing the surface speed of a wheel, it acts harder or softer. For instance, in a certain operation in which the wheel is running at 5,500 s.f.p.m. it may wear away readily and is said to be too soft, but by increasing to say 6,000 s.f.p.m. it may not wear away so quickly and yet cut just as well and thus becomes a relatively hard wheel. Conversely if a wheel *glazes* (too hard) this may be overcome by reducing the speed. For this reason as the wheel wears away its speed should be increased in order to maintain a constant surface speed, otherwise the smaller the wheel becomes the quicker it will wear away and become "softer" due to the gradually decreasing surface speed. It has been found that a change of 1,000 s.f.p.m. represents approximately a difference of one grade in cutting action.

The relationship between speed and true grade is that a soft wheel should be run (to prevent excessive wear) at a greater speed than a hard wheel which can revolve slower without being worn away so rapidly.

Owing to some confusion between *glazed* and *loaded* grinding wheels, it might be explained here that in a glazed wheel the cutting edges of the exposed abrasive grain are worn flat due either to too hard a grade of wheel being used for the work, or from lack of dressing, or operating it at too great a speed. In a loaded wheel the spaces between the grains are filled with the abraded particles; this often occurs when grinding soft materials such as aluminium, copper, etc., and can be largely overcome by using special filled wheels.

Wet Grinding

"Wet" grinding, as the name infers, applies to all grinding where solutions are used on the contact of the work and wheel; "dry" grinding being performed in the natural or dry state. Wet grinding has been done for the last 45 years.

Lubricants

A grinding lubricant, compound, or cutting oil is a liquid which does not function in the ordinary sense of lubrication, but is used to aid in the cutting action of the wheel and at the same time keeps the work at as nearly a uniform and low temperature as possible. Another function is to carry away the small chips and thus prevent glazing of the wheel. The solution should both cool and penetrate the cutting edges of a grinding wheel rapidly.

Although clear water is a lubricant, it rusts both the work and the machine, but this can be prevented by the addition of carbonate of soda. The use of "soda ash" solution has been in practice for a great number of years. A serious disadvantage of the soda is the trouble caused when it splashes into the operator's eyes, Some of the first grinding compounds produced to overcome this, had other objectionable features such as becoming rancid, germ carriers, etc. The specially prepared compounds of the present day are claimed to be free from these objections and to possess superior cooling and penetrating qualities. There are a number of these soluble oil and other compounds now on the market with which good results are obtained. Some of these are made from sulphurated fatty oils and mineral oils, the sulphur being said to have high refrigerating properties.[1]

These cutting oils being highly diluted with water, do not act as a film between the wheel and the work as the case of an ordinary lubricant which would hamper the grinding operation. The dilution is variable, an average being about 50 parts of water to one of the compound; for some operations as little as 20 parts of water should be added. Too large a proportion of the compound causes foaming, but this can be kept down with a little kerosene.

Applications. It is claimed by the grinding compound manufacturers that lubricants can be used with advantage in every case where grinding wheels having an insoluble binder are used. They should, therefore, not be employed with shellac or rubber wheels since the bonds are soluble in oil or alkali. Except in the case of the latter type wheels (*see also* cylinder cements, Table VIII), these lubricants are largely used for general precision and surface work and where tool-cutting is required. They are not, however, usually employed for rougher work such as snagging. The lubricant is supplied by a circulating pump and floods the work at the point of grinding contact.

The life of a grinding wheel as well as production is increased by the free and proper use of these lubricants.

Self-lubricating Wheels

For special purposes the wheel is heated to the temperature of the melting point of the filler, in which it is then immersed until the filler has penetrated the pores of the wheel. The wheel is then rotated at its working speed to remove the excess by centrifugal force. A filler sometimes used consists of a mixture of paraffin and common rosin.

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[1] Private information Sun Oil Company, Philadelphia, Pa.

Classes of Grinding

There are roughly two general classes of grinding, "off-hand" and "precision", both of which may be divided into three types which are mainly governed by the shape of the work, namely "surface", "cylindrical" and "internal", while these again have numerous sub-divisions.

Off-hand Grinding

Includes all rough grinding where quick removal of material is the main object and largely applies to the "snagging" of rough castings, also to some kinds of tool grinding.

Precision Grinding

Includes work requiring the utmost accuracy and exact limitations of the dimensions to specification. It thus embraces practically all operations calling for a high degree of accuracy and smooth finish and applies largely to many types of cylindrical and internal grinding.

Semi-precision Grinding. These operations include machine grinding which is also to some degree dependent upon hand manipulation. The results obtained are, however, not quite so accurate as those of precision grinding. Typical instances are the rough grinding of car wheels, steel rails, and the surface and internal operations on certain alloy steel products such as safes. Other typical operations are the slotting, cutting or surfacing of stone such as granite and marble, rough grinding of pearl buttons, etc.

The earliest and simplest form is straight "hand-grinding" where the work is held in the operator's hand—mainly used by small manufacturers or mechanics for grinding carpenter's tools, etc., or in the household for knives, scissors, etc.

The types of machines used for semi-precision grinding include swing frame, flexible shaft, portable electric, and pneumatic machines. The "swing-frame machines" are used for grinding large castings which are too bulky and heavy to be mounted on a stand, such as for grinding heavy locomotive parts, alloy steel billets, etc. The essential feature of this machine is a horizontal counter-balanced arm movable in all directions within limits of the arm, at the front end of which the wheel is suspended in a yoke carrying the bearings. A protruding handle or handles enables the operator to move the revolving wheel over the surface of the work and at any pressure he so desires. The work can be supported on a carriage so as to enable it to be moved backwards or forwards.

"Flexible shaft machines" are used to take wheels smaller than 10 inches diameter, the power to rotate the wheel being transmitted through a flexible shaft, the weight of the wheel and mechanism being supported by the operator who guides the wheel over the work. This is mainly used for snagging very large and irregularly shaped castings.

The "portable electric" grinding machines in which a comparatively small wheel is attached to a motor, are usually suspended by chain and tackle from above to take the weight, being guided by hand over the work. They are used for a large variety of work and are particularly useful for railway track and frog grinding or in shops and foundries for cleaning rough spots from large castings. A machine designed for removing corrugations on rails while in place is mounted on a tractor.

Cutting-off

For the cutting of such materials as metal tubing, piping, rods and general bar stock, very thin wheels having shellac, Bakelite, or rubber bonds are used and operate, in the case of the two latter, at 9,000 to 12,000 s.f.p.m. The very thinnest wheels used for the cutting of tungsten wire are operated in gangs, and have a hard rubber bond.

Types of Grinding

Surface Grinding

Although all grinding is surface grinding of some kind—either cylindrical, conical, or plane— the term is generally recognized as an operation which produces and finishes flat (not curved) surfaces. This applies to the large majority of operations from coarse grinding to the finest precision work, both for small as well as large surfaces. Two types of machines are used; in one the work table reciprocates in a similar manner to a shop planer and in the other, the work table revolves. Various types of wheels are used such as straight, cup, cylindrical, etc., these being mounted on vertical or horizontal spindles. The use of the magnetic chuck for the surface grinding of a number of rings or small parts simultaneously has been highly developed.

In plane surface grinding the speed of the work—either sliding or rotating is kept constant while the speed of the wheel is changed to suit the conditions—which is the reverse of cylindrical grinding.

Cylindrical Grinding

For this type of finishing the grinding wheel has largely supplanted the lathe tool giving more perfect cylinders at less cost than it was possible to produce with the lathe alone.

The modern cylindrical grinding machine is one of the greatest aids to rapid production as it will accurately finish a great variety of parts of all degrees of hardness. Cylindrical grinding is a trade in itself and to understand thoroughly the many problems involved calls for a knowledge acquired only by long experience.

Two methods are employed, namely, a stationary wheel and movable work carriage, or a travelling wheel carriage and stationary work. The latter is the older and commoner type, but for grinding heavy work the travelling wheel carriage is the more advantageous. Both plane and universal grinders are used, the former takes the place of the engine lathe for turned work both tapered and straight, whereas the universal grinder can be used for a wide range of work which includes, besides plane grinding, taper, cutter, face, internal, etc., and even surface grinding.

The speed at which the work rotates, in relation to the hardness of the wheel, has much to do with successful cylindrical grinding. Increasing the work speed stops the glazing of the wheel, while reducing the work speed counteracts the rapid wearing away of the wheel. Under general conditions when the grinding wheel is running at a surface speed of 5,000 feet per minute, the following work speeds[1] have been found to be satisfactory:—

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[1] Jacobs, F. B.: Abrasives and Abrasive Wheels, p. 223 (1919).

Cast-iron roughing, 40 f.p.m.; finishing, 50 f.p.m.

Steel roughing, 20-30 f.p.m.; finishing, 30-40 f.p.m.

The rate of traverse of both the wheel and the work are factors dependent upon size of wheel, its face, speed, hardness of work, and finish required.

The many factors involved in the art of cylindrical grinding are detailed in a recent publication[1] by the Norton Company.

Roll Grinding. Rolls vary from those less than a foot in length and diameter, such as used for rolling ribbon stock, to those up to 60 inches in diameter and 15 feet in length used for rolling armour plate and for use in paper mills.

It is estimated that a roll dressed by grinding has 50 per cent longer life than one dressed by turning and the dressing can be done in at least a quarter of the time.

Rolls are ground either by supporting their ends on centres or while rotating on their own journals. The first method is mainly used for light rolls, but in either case the centre must be dead accurate and the journals absolutely cylindrical. Specially built cylindrical grinding machines are used. For large rolls the work is fixed and the wheel travels back and forth over the surface to be ground. The rolls are usually rotated from 20 s.f.p.m. for the largest rolls to 2,000 s.f.p.m. for the smallest rolls used in cylindrical grinding machines, and the wheel from 4,500 to 6,000 s.f.p.m. For hardened steel rolls the special aluminous abrasive wheel is used and to produce a highly polished surface a silicon carbide shellac wheel is used. For cast-iron rolls coarse silicon carbide wheels are employed usually followed by a finer grit wheel.

Centreless Grinding. This comparatively new type of grinding occupies a very important part in the grinding field as by its means numerous (mainly small) round parts can be economically handled. The machine carries two wheels; a high-speed grinding wheel and a feed wheel revolving opposite it and forming a grinding throat (Plate XIII A). The latter wheel controls the speed of rotation of the work as well as regulates the feeding movement. The parts to be ground can be fed either by hand or automatically through a hopper. In the "through-feed" method the work passes axially between the two wheels, such as in the case of piston pins. With the "in-feed" or "shoulder" method used for two diameter work, the parts are fed into the grinding throat to a stop and ejected when ground to size. These machines have hydraulic controls both for the wheel slide and for the diamond truing device and will accommodate and accurately finish work ranging from $\frac{1}{32}$ inch to 6 inches in diameter. A string of 10 or 12 small parts, such as valve cam rollers, can be finished simultaneously.

Internal Grinding

This operation as the name denotes, concerns the accurate finishing of holes in such parts as bushings, gears, cylinders, cutters, gauges, etc. More accurate and satisfactory results are obtained by internal grinding, particularly in the case of hard alloy steel parts, than by the older methods of reaming and lapping from the rough. Holes can now be finished rapidly within a limit of 0·00025 inch or less directly from the rough boring.

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[1] "Grinding" published by Norton Company, Worcester, Mass., pp. 213-252 (1926).

Owing to the small space of internal work, the wheels used are usually small and stout; for internal grooving, recessing, or shoulders, cup and dish wheels are used. Universal grinding machines of the types described in cylindrical grinding are often used but are mainly confined to tool rooms as they are not so efficient as the internal grinding machines. There are two types of these latter machines, one where the work is rotated during grinding, the other where the work is stationary and the axes of the wheel rotate in an orbit, the orbit or circle being set for the inside of the cylinder or other type of work being ground.

Other Grinding Operations

There are many other grinding operations besides the above which are somewhat in classes by themselves. These include slotting, saw sharpening or "gumming", form grinding, glass, stone, and other non-metallic grinding. Besides these there are the more highly intricate types, such as crankshaft or those of tangential curves such as cams.

Saw Sharpening

The "saw gummer", as it is technically called, is one of the most important tools in the lumber industry and is used for sharpening hand, band, and circular saws. The "gumming" or deepening of the spaces between the teeth is performed by a grinding wheel (usually of the saucer type) mounted on a special machine which causes the wheel, set at the proper angle, to automatically move in and out of the tooth spaces while the band saw travels forward at regular intervals of time, the gumming and sharpening being done simultaneously. (Plate XIII B). For circular saws the teeth are rough ground on automatic machines to give them the proper shape, after which the saw is tempered. Great care must be taken to avoid running wheels at too high a speed or using too hard wheels, because of the danger of over-heating the tempered steel.

Form Grinding

The smooth surfaces of granite and marble employed for columns, monuments, mouldings, etc., are usually imparted by means of grinding wheels. In order to give the desired contour to the moulding, the grinding wheel face is previously dressed to the exact but opposite contours. Vitrified silicon carbide wheels are generally used. It is really a cylindrical grinding operation as the work revolves as in a lathe.

Flat Surfacing

When applied to stone, flat surfacing consists of grinding the rough surfaces of the slabs sawed from blocks. This is done on a coping machine using a wide faced wheel. The final surfacing is performed by means of a flexible rotating head machine using the side of the wheel.

COATED ABRASIVES

Coated or surface abrasives include abrasive coated papers and cloths known in general as "sand papers"; flexible wheels upon the face of which the loose grain is glued, and disks on the sides of which either loose grain or abrasive cloths are attached.

ABRASIVE COATED PAPERS AND CLOTHS

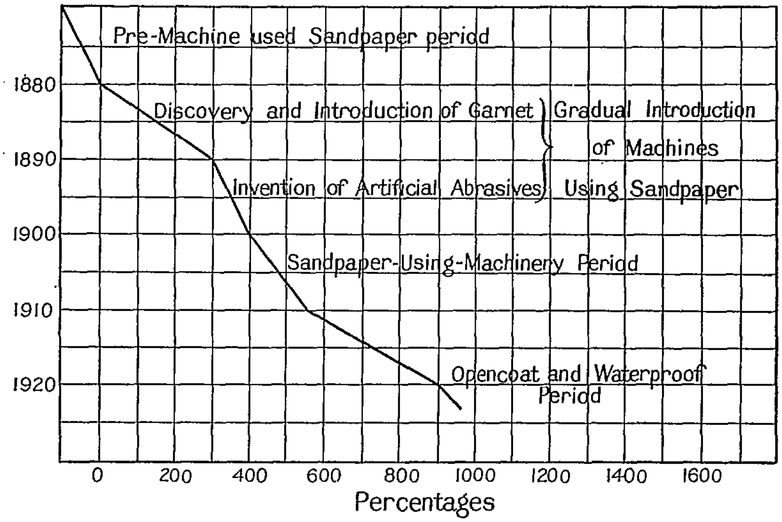
The term "sand paper" is a misnomer as abrasive papers are not made from sand. The natural abrasives used are corundum, emery, garnet, quartz or flint, and for some purposes pumice powder, while the artificial include silicon carbide, fused alumina, and some of the hard rouges.

Historical

The idea of the present form of surface abrasive was probably gained from the 12th century use of dried shark skin or splintered whale bone for scouring purposes. In the next century the Chinese attached crushed sea shells to a parchment with natural tree gum. Later, Swiss artisans used ground glass coated onto a parchment or hide. The abrasive qualities of sand have long been recognized, sand being used many centuries ago for such purposes as scouring wood floors or ship's decks. The gumming of sand and glass onto paper appears to have been started on a commercial scale by W. J. Davis & Sons, Ltd., Bermondsey, England, who have steadily been in business for 250 years and are believed to be the oldest abrasive manufacturing concern in the world.

Glass coated paper was first made in the United States about 1825 by hand-coating individual sheets; but a few years later it was made in strips, power being provided by dog-driven treadmills. Twenty years later the abrasive value of the New England flint (quartz) deposits were recognized and, in 1850, the first machinery for satisfactorily manufacturing coated abrasives was invented by the Baeder-Adamson Company of Philadelphia. Glass and flint were the only abrasives used until about 1875 when garnet was tried out. It was put on the market in 1880, but its superior sanding properties were not fully realized for another ten years when the finishing of hard woods became more general. Previous to this the largest consumption was in the shoe industry. In the early nineties corundum and emery were the only abrasives used on metals. The coated abrasive industry rapidly expanded with the introduction of coating, slitting, and cutting machines, as well as new and better abrasives, such as garnet for wood and later the artificial products for metals, along with the introduction of belt, disk, and drum grinders. In recent years the introduction of open-coated and waterproof papers has led to still further expansion in the industry.

About 50 years ago the United States production of "sand" paper was 200,000 reams valued at $750,000, and in 1926 was almost 1,180,000 reams valued at over $16,000,000. The large manufacturers of to-day are making over 8,000 varieties of surface abrasive units for use in almost every industry in which abrasives are employed. The inconvenience caused by this multiplicity of varieties induced the manufacturers, early in 1928, to agree upon a simplification of products which reduced the number of varieties by about two-thirds. This decision, though causing considerable difficulty in marketing the obsolete stocks, should, however, be eventually to the benefit of the public that uses coated abrasives. The progress of abrasive papers is graphically illustrated in Figure 10.[1]



Reproduced from Abrasive Industry, June, 1924.

Figure 10. Diagram illustrating the increase in the use of abrasive coated papers.

Manufacture

The materials used in the manufacture of abrasive coated papers are abrasives, glue, and the paper or cloth called the "backing" upon which the abrasive grain is glued.

The Abrasive

The artificial abrasives are received by the sand paper manufacturers in the graded form. Since, however, the sizing of the material for coated work requires more accurate sizing than for wheels, the products are generally re-graded. Each manufacturer varies slightly the small details of the sizing process, but the methods are essentially the same as already described, there being only a greater repetition of screening, intermittent crushing and magnetic separation.

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[1] Sidford, A. J.: "Sandpaper Industry is Reviewed"; Abrasive Industry, p. 151 (June 1924).

Recently some abrasive and sand paper manufacturers have given the grain a *special treatment* whereby the surface of each grain is roughened so that the glue will adhere more readily. One method of chemical treatment, of which there are several, is the etching of the grain by means of sodium fluorite.[1] Other acids are sometimes used to bring about similar results. A special retreatment of the alumina at a high temperature also hardens and roughens the grain.

The natural abrasives, such as garnet, are received as mixed (in size) concentrates and any impurities that may be present have to be removed by gravity methods, though this should not be necessary if sufficient care has been taken by the producers of the raw product.[2] The grading process for the natural abrasives is the same as for the artificial, but the requisite number of grades for each differs as shown in the chart of comparative abrasive grades, Figure 12.

The graded grain is kept in special sealed bins, free from dust and oily atmosphere, and warmed before being placed in the feed bin above the "making" machine in which the paper is coated. The cleanliness of the grain is of considerable importance since any coating on the surface of the grain will interfere with its adhesion. Its adhesion ratio is measured by its capillarity, the details of the test being outlined on page 39 of Part III. Warming the grain increases the power of absorption. By giving the grain a chemical treatment, the surface coating (which lowers its capillarity) is not only removed but the surface of the grain is etched, thereby giving it an abnormally high power of adhesion.

Glue

The selection and quality of the glue is of the highest importance, even more so than that of the abrasive itself, since the glue must be such that it will withstand the great wear and pulling forces to which the modern sanding machines subject the abrasive grains. If the grains are torn out before they are dulled or fractured, the paper or cloth becomes useless, no matter how good the abrasive itself may be. The proper glue should have high viscosity or adhesive power, strength to resist tearing action, and flexibility. There are several different kinds of glue such as cattle hide glue, bone glue, and blended bone and hide, of which first quality hide glue is the best.

The solid glue is melted in steam kettles to a temperature of not over 150°F. and is tested for viscosity; and for rigidity when cool; and is rejected if not up to standard. Only sufficient to last 24 hours is made up as the glue rapidly deteriorates, and disintegrates above 150°F. The liquid glue from the main kettle is piped by gravity to a steam-jacketted trough through which the roller imparting the glue to the paper revolves. The glue is kept at 140°F., and its consistency may be 1 part water to 1¼ glue by weight for very heavy work, and 2 parts water to 1 of glue for fine-grained papers.

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[1] Hartman, A.: U.S. Pat. 148792, Feb. 5, 1924.

[2] For details *see* Part III, Garnet.

The Backing

Where strength is required such as for garnet and for the artificial abrasives, a heavy Manila fibre paper is used which has been tested for strength, fibre, and flexibility; for flint or emery, kraft paper is used. For the cloth backings for metal work cotton drill of various compositions and weight are used. The drill is prepared by stretching on machines in lengths of 28 to 34 feet. The strips are then sewn together and saturated with clay and glue in order to fill the pores so as to make the cloth impervious to the coatings of abrasive and glue. The combination backings consist of paper and light cloth glued together, the abrasive being applied to the paper side, since the glue adheres more strongly to the paper than to the cloth. This is stronger than paper and stretches less than cloth alone, a quality that makes it specially suitable for belt sanding. The paper for "double face" consists of two thin sheets fastened together with a clay adhesive which enables the sheet to be easily pulled apart after coating.

The papers or cloths are done up in rolls of a thousand yards in length and are usually about 30 inches wide.

Coating Operations

A comprehensive idea of the "making machine" and the various steps whereby the coated papers are made may be obtained from Figure 11. A brief explanation follows: The roll of paper is first run through the automatic rotary printing press which imprints (in every square foot) the firm's name, trade mark, and grit number. It then passes through a heated aperture to warm it before coming in contact with the glue. The coating is done by passing the paper over the top of a rubber roller revolving in the steam-heated glue trough, thus making a light and continuous coating on the face of the paper, the thickness of the glue coating being regulated by an adjustable idler roller. (*See* Plate XIV A.) Immediately afterwards it passes under a vibrating brush whereby the glue is distributed evenly and the ridges smoothed out just before the sheet passes under the stream of falling abrasive. The grain pours from a large hopper onto a second steam-jacketted hopper that warms it before it passes through an aperture as long as the width of the paper, the width of the opening being determined by the size of the grain and machine speed. From thence the falling grain strikes a revolving distributor roll (usually also steam heated) and then onto the wet glued surface in a steady even shower. The travelling sheet then passes round a large steel roll and the abrasive is pressed into the glued surface of the paper. (This operation, however, is used only for the coarsest sizes.) The paper next passes over a revolving "kicker" or beater which knocks off all excess and loosely held grains. These fall down the incline of the paper and are caught and carried away as shown in the illustration by means of a cross belt. A large surface perforated drum connected with an exhaust fan creates a strong suction which grips the paper as the drum rotates and pulls it out of the making machine; this further serves to iron out any wrinkles. The paper is then automatically conveyed up to the roof by means of wooden slats which are caught up by stops of an endless

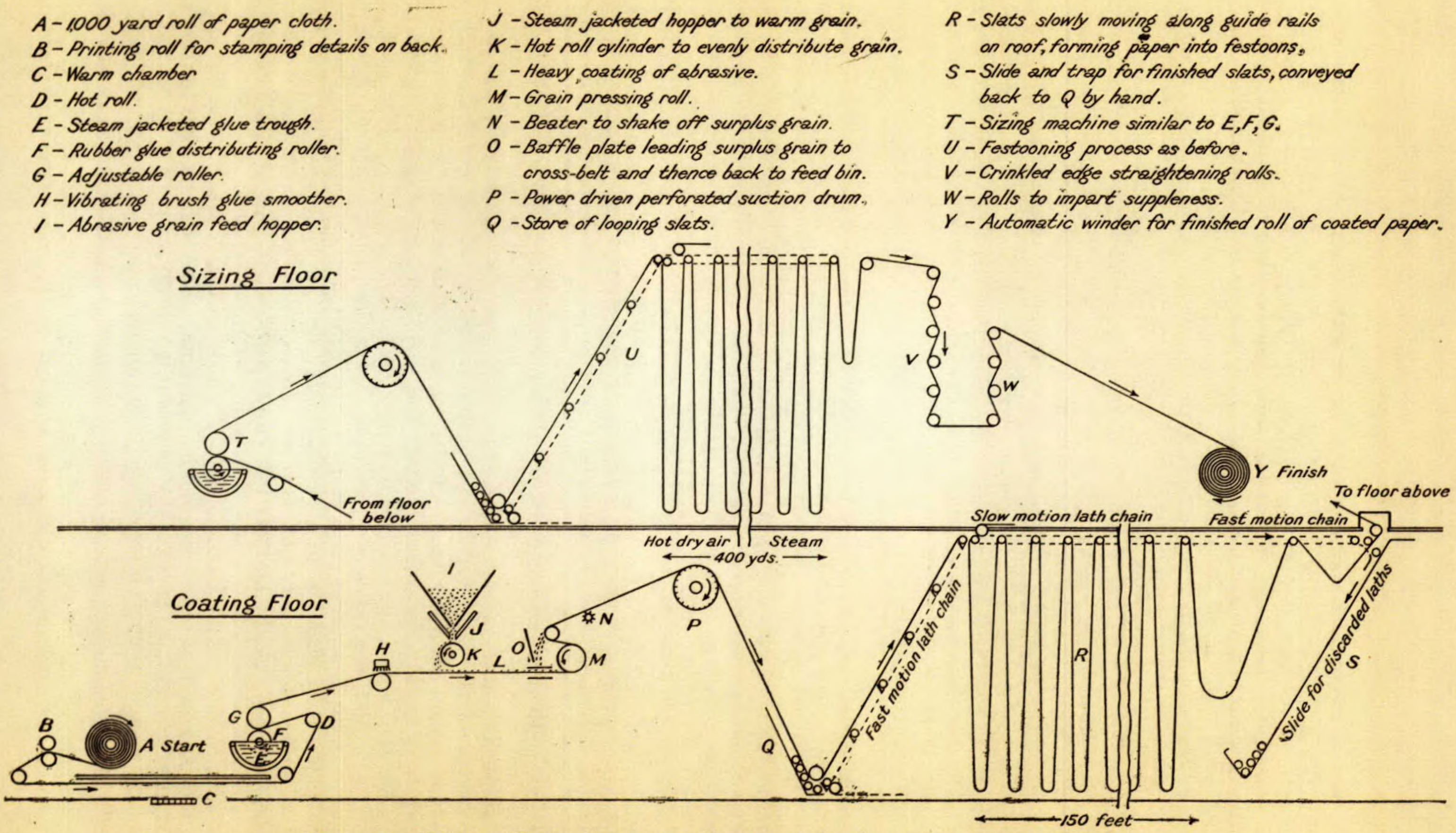


Figure 11. Diagram illustrating the manufacture of abrasive coated papers and cloths.

chain, and encounter a slow motion chain, causing the faster moving paper behind this chain to form into festoons about 17 feet high. These traveling hangers are very slowly carried along for about 150 feet over hot air vents. (*See* Plate XIV B.)

The next process is the second coating of glue or "sizing" operation. At the end of the run the rate of travel is automatically increased and the paper then passes through the re-gluing trough in the same manner as before, but the glue is much thinner, being about 5 parts water to 1 part glue. This top coating ensures a thorough and complete surrounding of each grain by the glue and anchors it to the next so that the finished paper will withstand the friction of sanding. The first glue coat only holds the grains on the backing and does not retain them against lateral pressure. After passing through the sizing machine the material is festooned in racks as before, slowly moving over a continuous flue from the apertures of which dry hot air is sucked upward to a ventilating system, thus ensuring continuous circulation necessary to proper drying. As the line reaches the end of its journey it is subjected to enough steam to soften the paper sufficiently so that on passing in and out of a series of parallel rolls set close together the paper is stretched and the crinkled edges are straightened out. It then passes over more rolls to make the paper more flexible. Finally every 1,000 yards of coated paper is wound up into a roll, the drive of which is automatically regulated to keep the speed of the continually increasing periphery constant.

There are many conditions which must be considered to make a product of uniform quality. The paper is not of uniform thickness and therefore the space between the gluing rolls must be adjusted; various kinds of papers absorb different proportions of glue. The absorption value of an abrasive varies according to size as well as to the nature of the abrasive; the viscosity of different glues varies and has to be constantly checked. Taking these into consideration the uniformity of abrasive papers must depend largely on the experience and skill of the making-machine operators.

Cutting and Packing

After a week of natural seasoning the finished 1,000-yard roll of coated paper is brought to the cutting floor where it is split into the numerous lengths and sizes required. If the standard 9- by 11-inch sheets are required, the roll is unwound and the paper passed under four circular revolving cutting knives which trim the outside edges and slit the three strips 9 inches wide. Every 11 inches of each length is automatically cut across by a large knife. These cut sheets are removed by three endless belts which automatically collect 24 sheets (one quire) and move the batch forward to the inspection and packing department. After having passed inspection they are done up in quarter ream bundles of 5 quires. Various other sized sheets are cut, but 9 by 11 inches is the general standard. Rolls are done up in 50-yard lengths from full width of 27 inches (48 inches for garnet paper) or any of the twenty different widths down to narrow strips of $2\frac{1}{2}$ inches.

Numerous sizes and shapes are required by some trades, such as the shoe industry which necessitates the cutting of different strips of $\frac{1}{2}$ to $2\frac{1}{2}$ inches, most of which have to be moulded to various shaped curves in cross-section (*see* description of shoe trade).

Manufacture and Uses of Special Papers

Double-faced Papers

These are used as "finishing" papers and are very lightweight, thin papers made up in fine grits of 0 to 7/0 or less than 280 mesh. The material, as used, would be too thin to withstand the strain through the making machines and subsequent handling, so that special papers are made up in two plies and coated with the glue and abrasive on both sides—first one side, and, when dry, on the other—these can readily be separated to form two very thin flexible sheets each coated on one side with the abrasive.

Double-faced papers are done up in packages of 240 sheets which on splitting become the standard 480 single-faced.

Open-coated Papers

These papers, which were first introduced in 1918, have open spaces between each grain ("chip clearance"), and are mainly used in the woodworking industries and on painted surfaces. These papers are very free-cutting and possess a high degree of flexibility, but their main advantage is that the tendency to clog is reduced to a minimum since the abrased particles have a better chance to collect without interference, or to fall away. There are four standard degrees of closeness of the grain—"very open" used only for gummy material; "full open" for paint jobs; "medium open" for leather, soft wood, etc.; and "slightly open" for harder woods or medium hard non-metallic surfaces. Although these papers have high cutting speeds, if the chip clearance is too great the cutting is reduced on account of the reduction of the abrasive so that the best efficiency depends on using the proper type for the material to be surfaced. These open-coated papers or cloths are principally made with alumina abrasive and are to some extent replacing the natural garnet for hard woods.

The uniform distribution of grit necessary for the production of these papers calls for great accuracy and precision. The flow of the grain is in some cases mainly controlled through the feed hopper at the bottom of which trays are inserted having a calculated number of holes or slots spaced at definite intervals. Different sets of trays produce the different degrees of closeness of grain. The speed of travel of the sheet is also a controlling factor.

Waterproof Papers

As the name implies these papers are used in conjunction with water. In "oil sanding" ordinary glue papers are used with oil, but would quickly disintegrate in water. The waterproof have many advantages over the normal papers in that they are dustless and the solution employed washes away the grindings so that they rarely clog and consequently are considerably more efficient. The liquid lubricates the action of the abrasive and produces a better finish than by dry sanding. Plenty of water should be used as it hardens the surface being sanded resulting in a smoother finish. Waterproof papers have a high degree of flexibility when wet, but if used dry they break more readily than ordinary papers resulting in loss of time and material.

Waterproof papers are primarily used in all paint, varnish, and lacquer surfaces and find very extensive employment in surfacing automobile bodies.

The use of these papers has rapidly increased until it now amounts to almost 20 per cent of the coated paper industry. This increase is coincident with the increased use of pyroxoline finishes, such as "Duco".

The main difference in their manufacture lies in the adhesive, which is naturally not glue. The mixture used by the different companies appears to be trade secrets, but a mixture containing Chinese nut oil and linseed oil is sometimes employed. The paper is waterproofed on both sides.

Abrasives and Their Main Uses in Coated Papers

Information covering the occurrences, properties, and uses of the natural abrasives will be found in Parts I, II, and III.

Flint

True flint rarely occurs in commercial quantities on the American continent, the material so-called being crushed quartz obtained mainly from the New England states. Up to 1875 this mineral was supreme in the coated abrasive field, since when its use has steadily declined with the introduction of harder and better materials. The United States production in 1926 reached a low record of 269,000 reams.

It is the cheapest of all the sand papers, the main demand being from the small user for hand work, and forms the bulk of the jobber's stock. Its main industrial use is for sanding surfaces which fill up the paper before it is worn out, and since all types clog up soon after starting on soft work and become useless, the cheap flint is the most economical. For this reason the painter and the worker of soft gummy woods are amongst the largest users. Flint paper is not used on sanding machines as it does not have the cutting property of the other coated abrasive products. "Pouncing paper" is either made from ground pumice or sometimes flour quartz and is used by the hat manufacturers for raising the nap on the felt or silk.

True flint paper is made extensively in England from the flint pebbles that occur abundantly in the chalk. This flint is tougher than that found in America and equals garnet but is not so sharp. It is an opaque grey colour in comparison to the glass-like quartz.

Emery

The Turkish variety of emery is more suitable than the Greek and better than the American and is now mainly used in the fine grits. At one time it held a similar position as a coating for cloth, as did flint on paper. The term "emery cloth" still often used in the trade, does not refer to the true emery but generally to silicon carbide. In appearance emery cloth is somewhat similar to the carbide product but the former is a grey-black in colour and often mottled due to impurities and lacks the high lustre of the artificial abrasive.

The manufacture of emery papers and cloths is steadily and rapidly declining, the United States production in 1926 being 43,000 reams which was half that of 1920 and is by far the smallest output of the ordinary types of papers. A very fine grit emery is coated on a soft, blue paper backing known as emery polishing paper and this is used in the jewellery trade, and by electrical appliance and other manufacturers for rubbing and polishing the softer metals.

Corundum

Natural corundum, when pure, is a highly satisfactory abrasive—both for metal and wood—in so far as its toughness and hardness are concerned. Unfortunately, its tendency to split into slivers and parallel-sided fragments has resulted in its use for coated papers to be entirely discontinued—at least on the American continent. About 20 to 25 years ago, before the superiority of the artificial corundum was so universally established, there was quite a demand for the natural corundum papers in the metal, tannery, leather, and wood-working industries. Corundum papers are very similar in appearance to the English flint but can be distinguished by the black-coloured specks in the former.

Garnet

At present the best abrasive garnet comes from the Adirondack mountains in New York state. Its introduction in 1880 supplied a long-felt want as a suitable abrasive for the sanding of certain products, particularly hard wood, and it still holds first place in the wood-working industries, though in the last year or two it has been replaced to some extent by open-coated alumina papers and cloths.

The sheet paper is generally used by the large furniture, cabinet, and piano manufacturers for hard sanding by hand. The roll paper is used on belt, drum, or disk sanding machines both for sanding and finishing of hard wood. The cloth is employed by the same class of trade as the paper; and the combination for belt sanding where an extra heavy, non-stretching material is required.

The garnet paper and cloth production in the United States is the highest of any individual type of coated paper and in 1926 amounted to 469,000 reams which was, however, a slight drop below the previous peak year of 517,000 reams.

Aluminium Oxide

The use of this abrasive for coating papers has considerably increased during the last ten years and is particularly adapted to the grinding of harder metals such as steel, cast iron, wrought iron, etc. Its increase in use is coincident with the great increase of the automobile and kindred industries in which waterproof papers are so largely employed.

Silicon Carbide

Silicon carbide papers and cloths are largely used for metal work, particularly for metals of low tensile strength such as aluminium, brass, copper, etc. These papers hold first place in the leather and shoe industries, and as a waterproof paper for hand rubbing it has a fair demand. The glue, however, does not adhere readily to this abrasive, due, it is believed, to an interference film forming on the surface of the grain, and also to the glassy smoothness of some of the splinters. This, in the past, caused excessive dislodgment of the grains, but has now been largely overcome by special acid treatment of the grit before application to the cloth; also by mixing in a little emery to act as bonding agent.

Crocus

Crocus, a hard purple-red rouge, is used on paper or cloth for the final polishing operation where fine finishes are desired in metals, and for cleaning where the cutting away of the metal would be objectionable. It is made in only one degree of fineness.

Glass

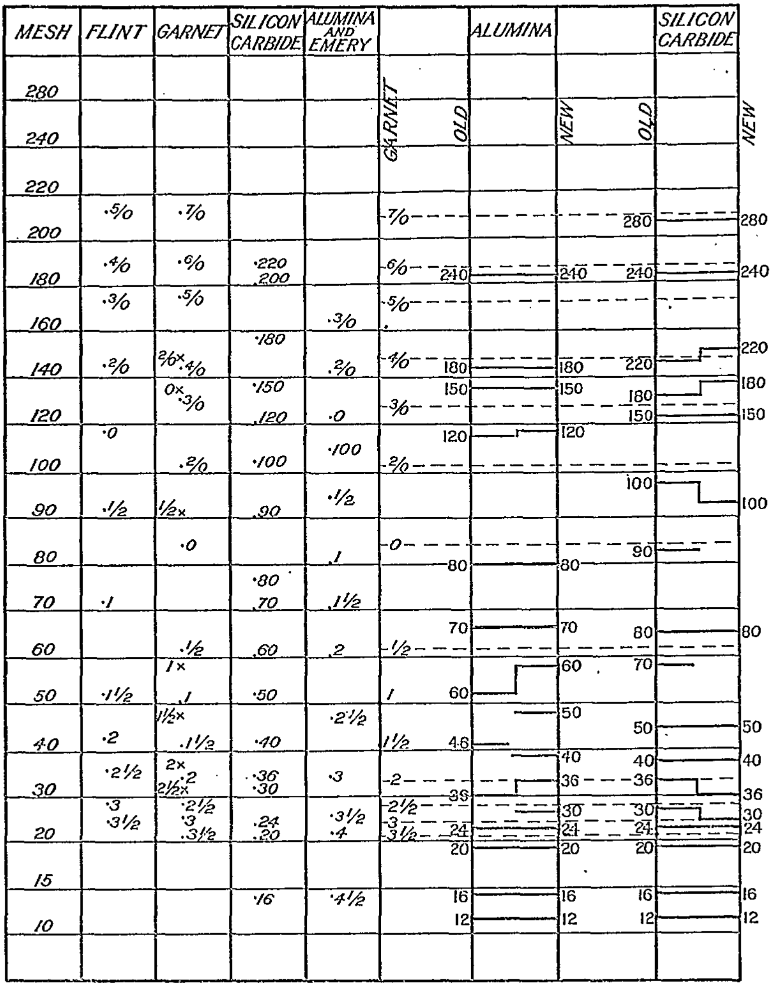
Pulverized and graded glass is used on paper to some extent in Europe where it is employed instead of flint paper for hand-surfacing of soft woods. It is now rarely used on the American continent.

Standardization of Grain Grade for Coated Papers

There is considerable confusion as to the comparative grading of abrasive grain. The same symbol in two different abrasives does not necessarily mean the same sized particles.

Attempts have been made towards standardization in which grades are compared by effective grain size instead of screen mesh, due to variations of shape and fracture. Thus different kinds of minerals that have been passed through the same screen do not have exactly the same grain size. The comparison by effective grain size is more accurate than by screen mesh.

The accompanying chart, Figure 12, shows the old and proposed new gradings.[1] The three abrasives, garnet, aluminium oxide, and silicon carbide now have the same test screens for corresponding grades. One set of garnet standard sands is maintained and all three material grades must conform to these standards. The alumina is also sometimes symbolized by fractions and is the same as the garnet.



Manning Abrasive Co, Inc, Jan, 1922
· Standard Grading
× Barton's Grading

Abrasive Industry, July, 1926
Compiled by A. J. Sidford

Figure 12. Comparative old and new grading charts for abrasive grains.

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[1] The latter was prepared by A. J. Sidford, Herman Behr & Co. *See* Abrasive Industry, p. 218 (July 1926).

Testing Abrasive Coated Papers

A simple device for comparing the strength of different makes of papers or cloths is to cut sample lengths, 9 inches by 1 inch, and clamp the ends between two flat wooden jaws. These are suspended vertically about 5 feet from the ground, the top jaw being fixed and a tray attached to the lower one upon which weights are placed until the test sample between the two jaws breaks. The ends of the paper should extend about 2 inches in the jaws of the clamps. The breaking strain per linear inch can be calculated from the total weights added. The strongest paper will naturally take the most weights before breaking.[1]

The nature of the grit can be examined by boiling 1 square foot of unused paper for about an hour; this detaches the grain from the backing. The freed grain is washed and examined under a lens for fracture, impurities, shape, or grading. The magnetic impurities in garnet can be separated out from the dry product by means of an ordinary magnet and their percentage calculated by weight or volume.

A practical test can be performed at the plant by taking abrasive belts of different makes but of the same grit, length, and width, and running them on test pieces of wood. Measured and weighed blocks of the same kind of wood are applied to the face of the running belt at a constant pressure and for similar lengths of time when they are then re-measured and weighed, the best cutting product being the one that cuts off the most material in the given time. This test is then repeated with the same blocks until each belt is worn out or ceases to function, when the total time of run is noted, the best belt being the one that lasts the longest. Disks and drum sanders can also be used for these tests but more labour is evolved in fitting on the different disks or coating the drums. The worn belts can be examined to ascertain whether the abrasive is worn down or torn out due to improper gluing.

FLEXIBLE GRINDING AND POLISHING

Flexible grinding is grinding performed by means of flexible wheels usually made from cloth or leather on the face of which the abrasive is glued. There is a gradual mergence from grinding proper to polishing and to buffing. The principal differences lie in the coarseness or fineness of the abrasive used and the method of its application to the wheels. When a bright finish is to be produced the action becomes one of "buffing" performed on somewhat similar but softer wheels. There is no standardized distinction between these operations and consequently there is considerable confusion of the terms used. The essential differences are as follows:—

Flexible grinding is removing the surface from forms, usually of uneven contour, which are difficult and often impractical to grind with solid wheels. The flexible wheel will "spread" and conform to the surface irregularities and may include coarse work involving the removal of considerable material, but more often prepares the surface for the polishing operation.

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[1] Jacobs, F. B.: "Abrasives and Abrasive Wheels"; Pub. by N. W. Henley Publishing Co., N.Y., p. 171 (1919).

Polishing is the production of lustre by removing tool marks, scratches, and other unevenness from the metal surfaces. Polishing is divided into three classes of operations: roughing, dry polishing, and finishing; the difference depending on the coarseness or fineness and type of abrasive used. Various non-metallic substances such as stone, rubber, ivory, glass, etc., are also finished by so-called polishing; but pads are usually used and the abrasive is applied in the loose form with water and not attached with glue.

Buffing refers to the finer forms of polishing whereby the slight irregularities are removed which generally remain after the first polishing operations and differs from polishing in that a soft abrasive such as tripoli or rouge is used on a flexible wheel (usually of cloth), the bond being a wax compound. Buffing operations are described later.

Manufacture and Setting-up of Polishing Wheels [1]

Historical

The first polishing wheels appear to have been wood covered with leather. Later, disks of leather were cut to the required shape and glued together, followed by the sewing together of many disks made from discarded sail-cloth. This in turn led to the manufacture of wheels made in a similar manner from disks of sheepskin, shortly followed by the one-piece solid felt wheel cut from sheets of felt.

Improved forms of all these wheels are used to-day, but the most important step was the invention of the compressed polishing wheels having iron hubs, steel body plates, or outer rings of leather and other materials. This gives the desired rigidity in the body of the wheel, with the positive control of the various degrees of flexibility required.

Types of Flexible Polishing Wheels

Most of the compressed wheels are made either of leather or canvas, but walrus hide, sheet felt, canvas, and rubber belting composition, paper, woven felt, cork, etc., are often used. Wheels are also made from these materials either in the solid form or as disks or strips glued or sewn together.

COMPRESSED WHEELS

These wheels differ from all the older types in their construction and action.[2]

> The principle is that of compression and reaction; compression, to generalize the elements comprising the cushion into a practically homogeneous mass and to permit control of various degrees of density; reaction, to give the wheel "life" or resilience through centrifugal force when the wheel is revolving. . . . . The life of the wheel in motion is the reaction from compression, and it is this reaction that the operator pushes against. . . . .
>
> In building the compress wheel flat blocks of leather, canvas, or other materials are assembled radially into a ring considerably larger than the diameter of the finished wheel.

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[1] Information largely supplied through the courtesy of Divine Bros., Utica, N.Y., and from their numerous publications and catalogues.

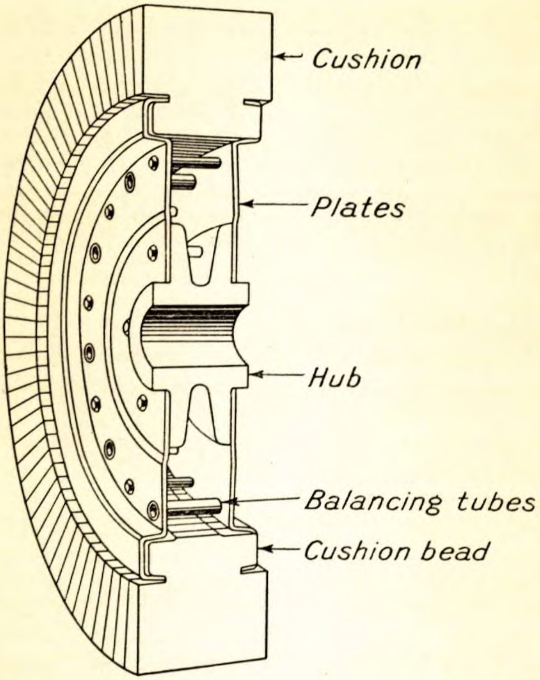
[2] "Abrasive Metal Finishing", published by Divine Bros., Utica, N.Y., p. 31 (1926).

The blocks are placed lengthwise across the face of the wheel parallel to the arbor hole. The edges of the blocks form the face of the wheel.

When canvas or other textiles are used the material is cut on the bias to avoid ravelling. The thread ends are thus presented to the face of the wheel.

The use of leather blocks permits the selection of pieces of uniform density of which to build the leather cushion. Hides vary greatly in density and porosity throughout their different portions, and it is necessary to use small portions of many hides to secure sufficient pieces for a wheel. The arrangement of these pieces to blend them, and the application of pressure, equalizes the density of the cushion throughout. The end grain of the leather is presented to the wheel face.

This ring of assembled material is reduced in size from the over-sized diameter, to the approximate diameter of the finished wheel, by circumferential compression. The compressed ring of material is held in place by a metal holding ring around the outside until the wheel is practically finished.



Courtesy Divine Bros.

Figure 13. Section through compressed flexible wheel.

The compressed material is now tooled to fit the annular grooves in the metal side plates. The hub is machined to accurate dimensions before assembly. The arbor hole is bored and reamed, ensuring a perfect fit to the machine arbor.

The side plates are carefully fitted to the bead, one on each side, and the hub is placed between the plates at the same time. Cushion, side plates, and hub, are all brought together under pressure. When in place, the side plates and hub are riveted together, forming a strong solid unit at the centre, which locks the cushion securely in place. The illustration of a compress wheel, cut in half (Fig. 13) shows the rugged construction.

At this point, the metal holding ring is removed from the wheel which is then mounted on its own centre, and the face of the wheel turned and shaped (or formed) while the wheel rotates under speed. Balancing tubes are riveted in, the wheel painted, and inspected. It is then ready for shipment.

The circumferential compression referred to above is brought about by squeezing the wheel through an iron cone by means of a hydraulic ram, the small tapered end of the cone being the required reduced diameter of the wheel.

The depth of the cushion varies from 1 to 3 inches, and width of face $\frac{1}{4}$ to 4 inches.

Owing to their strength and high factor of safety it is not necessary to make these wheels over 24 inches in diameter, since any desired peripheral speed may safely be attained.

The range of work which can be done on wheels of this type covers almost the entire field of polishing, though each type of work calls for a specially designed wheel.

The oak-tanned *bull neck* leather wheel is used for all general purposes, from the coarsest roughing to the finest finishing. This leather is softer, more spongy, and has a more open grain than back leather. The *canvas wheel* also has a range of work about equal to that of the bull neck and is also specially suited to oil or grease work. The *composition* wheel built of canvas duck and rubber belting holds the coarser abrasives firmly in place and is well adapted to the roughest and hardest work such as in heavy castings. The *walrus* hide wheel owing to its open grain and velvety face is used for very fine finishes, and is extensively used in the silver and jewellery trades. The *felt* wheel is now being replaced by the canvas wheel for the finer classes of finishing work, the cushion being particularly elastic. The *wool felt* wheel owing to the cellular condition of the fabric permits the glue to penetrate and hold the abrasive grain with unusual strength. They are stiffer and hold a flatter face than the canvas wheel. The *paper* wheel, made from strawboard paper, being very uniform and true-running, is an accurate hard-faced wheel especially suited for flat precision surfaces. The *sheepskin* wheel has an extremely soft, close-grained face by means of which the very best quality finishes are obtained such as for precision tools, surgical instruments, fine gun parts; it is also used in the jewellery trade. This wheel is used both for polishing and buffing. *Strap faced* wheels have a leather strap around the periphery of either leather or paper wheel. They are largely used in England for a wide range of polishing work. Prior to the invention of the compressed wheel the solid wooden wheel with a leather strap around the face was the most popular, and the oldest type of polishing wheel. Its main application is where the surface must be perfectly flat and the corners left sharp.

SOLID AND NON-COMPRESSED WHEELS

Disk Canvas Wheels. The construction of these wheels is as follows: Linen or canvas sheets, about 15 feet long and 4 feet wide, are laid out on a bench and small odd-shaped pieces are placed on top of the first sheet, but not overlapping one another. These are covered with another long sheet and more odd bits on top, but with thread at right angles to the lower layer, and the operation repeated until 20 or 30 rows are obtained when the top long piece is put in place. The material is kept moist and since the pieces lie flatter it is easier to manipulate in the later operations. The whole blanket is then rolled up till ready for disking, when the moist bundle is unrolled and the desired size of wheel is cut out by means of a circular die machine fitted with centre punches. The sewing may be either "open" or "close." In the former there is only one row of stitches close to the centre hole, while in the close wheel the stitches are made spirally, by means of an automatic machine from the centre almost to the circumference. Other types have three or four concentric rows.

The best canvas wheels are not made from scraps, but each disk is put on separately with a slight turn so as to ensure a continuous "cross-graining," while others are built up in series of folds. The above types are mainly used for buffing, but for polishing, the canvas wheels are usually provided with metal plates bolted through the sides, or sometimes with a series of bolted metal rings. For many purposes every two or three disks are sewn and each lot glued together. The flexibility of these wheels varies according to their proportion of sewing and gluing. This type is largely used for the coarse polishing of cast-iron or cast-steel parts.

Disks of bull neck leather, sheepskin, Spanish grey or Mexican grey felt, wool felt, etc., are sewn together and made into polishing and buffing wheels.

Solid Wheels. These are made of walrus hide, wood faced with leather, paper disks glued together, and various other combinations.

The various types of flexible wheels used for polishing are shown in Plate XVI.

Setting-up of Flexible Wheels

The finished wheel ready for use consists of any one of the types of wheels just detailed and the abrasive which is coated onto the face of the wheel with glue. The most important item of these is the glue.

THE GLUE

The importance of properly selecting and applying the glue cannot be too highly stressed since no matter how good the wheel or abrasive may be, poor results will be obtained unless every precaution is taken with the adhesive. The very best glue, which is made from a special class of hide stock, should be used. It should possess high viscosity, strength, toughness, and flexibility. The necessity for this will readily be appreciated when considering the tremendous tearing force applied to the grain when the wheel is revolving against a hard metal at 2,200 r.p.m.

Mr. B. H. Divine, who has spent years of study on glues for abrasive use, has published a book on the subject.[1] The essential points are reproduced in condensed form by the Norton Company's publication[2].

Although all the recommendations should be carried out in detail, some of these which are often overlooked include: overheating the glue, which disintegrates at 150°F.; reheating glue once used; keeping too long, sometimes over night; and cleanliness. Glue adheres less readily to aluminium than to any other metal, and aluminium pots are therefore easier to keep clean. Complete glue stands and automatically controlled heaters are specially made for this work.

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[1] Divine, B. H.: "The Use and Treatment of Glue for Polishing"; Pub. by Divine Bros., Utica, N.Y.
[2] "Grinding": Pub. by Norton Company, Worcester, Mass., p. 404 (1926).

THE ABRASIVES

For flexible grinding and polishing, either emery or aluminium oxide is used. Sometimes with the latter a little finer grit emery is added to assist in the binding. For grinding purposes the latter is preferable, but for the finer polishing work emery, usually Turkish, is used because the impurities present render it less harsh and therefore a better polish is possible. Greek emery is harder and therefore more economical work is attained by the artificial abrasive, but American emery being the softest and impurest of all the emerys is sometimes used for fine polishing. Silicon carbide is rarely employed, mainly because the grain will not adhere readily to the glue and is therefore comparatively easily torn out. This is, however, overcome to a certain extent by mixing in about 25 per cent emery of a finer grade which acts as a bond. In addition the carbide, being brittle, is not so suitable to metals of high tensile strength.

The grades of abrasives used for the three classes of polishing operations are as follows: *Roughing*, for which grits from 24 to 50 are used, more particularly 36 to 40; *Dry polishing*, for which 20 to 120 grits are used, but generally the coarser. Both operations are performed dry except in the case of aluminium when grease is used on the face of the wheel; *Finishing*, or as it is sometimes called "oiling", in which 120 grit to the finest flour grades are used. Generally, though not always, the wheel is greased with oil, beeswax, tallow, or some other similar substance, this oiling being performed during the polishing operation. In some cases the once used wheel face is coated with charcoal and then polished with a piece of flint or suitable stone. Such a wheel is used for imparting a high polish on hardened steel.

THE SETTING-UP

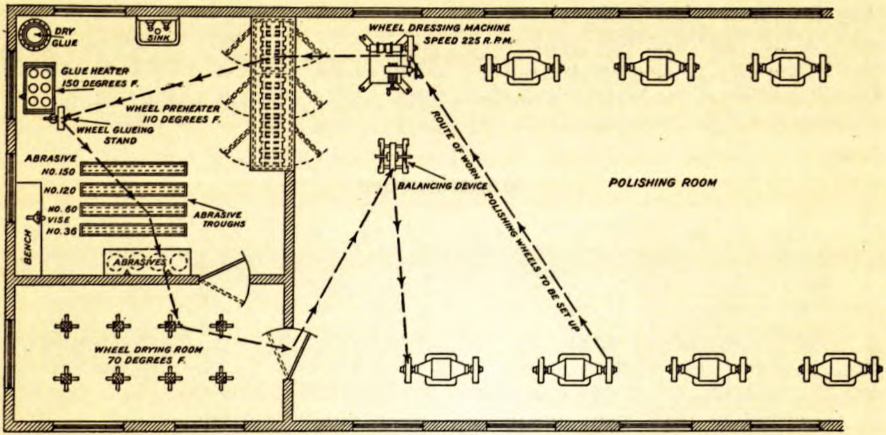
The "setting-up" or coating the abrasive onto the wheel is almost invariably performed by the user, the method employed being as follows:—

The new wheel is first heated to about 110°F. and then rotated in a lathe shaft when the face of the wheel is dressed or roughened to form a nap. The nap so produced is laid with a thin coat of glue by means of a brush. The excess glue is then thrown off by revolving at normal working speed after which the wheel is set to dry and then a second coating of glue is applied. The wheel is then immediately rolled evenly and with considerable pressure in an abrasive filled trough, which should be longer than the circumference of the largest wheel. The grain is kept at a temperature of about 120°F. and the troughs are usually steam-jacketted.

The wheels are then set aside from 24 to 48 hours for the glue to set before using. Sometimes two coatings of abrasive are applied.

Setting-up should be done in a special room, kept at an even temperature (about 70°F.) and away from the polishing room. The same brush should be used only for one grade and type of abrasive, so that no coarse grains will be accidentally attached to the wheel in which a finer grain is to be applied. Each grade of abrasive should be kept in well-covered boxes or trays in order to avoid any coarse grains mixing with the finer. Great care should be taken to avoid all draughts, particularly during the drying period.

Plate XVII illustrates the method of rolling in the abrasive, the covered troughs, and the drying of the wheels. Figure 14 shows a typical layout room.



Courtesy Divine Bros.

Figure 14. Typical polishing, glue, and wheel-room layout.

Application and Advantages of Flexible Grinding and Polishing

Some of the applications of flexible grinding are embodied in the description of the various types of wheels. In general this grinding is mainly done on uneven or curved surfaces, typical instances of which are found in agricultural implements such as ploughs.

As a general rule polishing is done, either for purposes of appearance, that is to produce lustre, or to prepare the surface for plating, painting, or stamping.

Polishing wheels are now made with a variety of shaped faces to conform with the concave surfacing, corners, recesses, etc., in the different designs of work. During recent years these form-faced wheels, improvements in the design of the wheel, and other factors, have resulted in the supplanting of the solid grinding wheel by the flexible grinding or polishing wheel for many classes of work. The work produced by the latter is economical since it does not leave a wavy surface as in the case of the solid wheel, thus reducing the number of operations, also a finish is produced on sheet metal or on uneven surfaces such as stove tops with a minimum removal of metal.

BELTS

Endless belts, usually made from canvas, are used for certain polishing operations. They may be supported on leather belts and sometimes cushion wheels are used as a backing for the belt.

DISK GRINDING

Grinding by means of a disk wheel, to the side of which either an abrasive or abrasive cloths are fixed, is now becoming a common practice and this tool has in many cases supplanted the grinding wheel or lathe. All the known hard abrasives are employed and both metals and non-metals are successfully ground by this method. With grinding disks the factor of grade as applied to grinding wheels is eliminated; it merely being necessary to select a satisfactory abrasive, the character of the desired finish determining the grain size of the disk.

Manufacture

There are several different types of disks and processes of manufacture. These include abrasive paper or cloth disks attached onto the side of wooden or iron wheels with glue or special cement. They are of varying thickness and are made plain or with grooved faces.

The first disks appear to have been invented by F. N. Gardner, Beloit, Wis. These were made from emery cloth by the Herman Behr & Co.,[1] and are known as glue-bonded disks, but it was the advent of the thick abrasive disk that resulted in considerable advancement in disk grinding practice.

The glue-bonded disks are now made by extra heavily coating artificial abrasives on a backing of heavy cloth or paper. They are cut from the sheets by means of large dies in a hydraulic press. A circular iron plate, called the "disk plate", is first washed with a strong lye or caustic soda solution and after rinsing in hot water is allowed to dry without handling the face or allowing it to come in contact with oily water. Special disk cement is applied to the plate until the grooves with which it is provided are evenly filled and then the back of the disk is coated until it has absorbed its capacity of cement. The disk is then placed on the plate and covered with a felt pad or similar cushion and clamped tightly in a press. It should remain in press for 24 hours and be allowed to stand in the air to dry thoroughly for at least 48 hours. The finished disk is then trimmed and usually dressed before using. When in storage the disk should be laid flat in a dry place with weights on top to prevent curling.

Types and Uses of Disks

The lighter forms of garnet coated disks are used for wood sanding and are briefly described under that heading.

Recently, very heavy abrasive cloth disks have been made from $\frac{1}{4}$ to $\frac{3}{8}$ inch thick, a distinctive feature being deep corrugations or a spiral groove that extends across the face while others have deep perforations or holes that penetrate to the backing. These grooves or perforations have several advantages over the solid type in that they minimize friction and thus prevent excessive heating, and enable the grindings to escape, thus preventing clogging. The cement or sulphur-attached disks can be used wet.

These heavy disks are made in numerous sizes and grits from 4-inch to 53-inch diameter and 150 to 8 grits of either silicon carbide or aluminous

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[1] Gardner, F. E.: "Development of Disk Grinding"; Abrasive Industry, pp. 362–365 (Dec. 1926).

abrasive. The lighter disks are made from flint, emery, and garnet from 3/0 to 3½ grits. These do not include the tiny disks used in the jewellery trade and for dental work.

Double-faced corrugated disks are now made with silicon carbide on one side and alumina on the other, so that they can be conveniently used for grinding either iron or steel. These are now largely employed by manufacturers of harvest machinery and allied products.

It is beyond the scope of this report to attempt to suggest when and where disks should be used in the place of grinding wheels, but in the present day the disk, in most instances, is either one of the principal or auxiliary grinding tools where the wheel is employed for the grinding of all metals, and finds extensive use on various non-metals, particularly for wood sanding.

SPECIAL SANDING OPERATIONS

Wood Sanding

Sanding practice varies widely in different shops, usually softer woods and those having an ornamental grain such as mahogany are sanded less and treated with finer grit than walnut or harder woods.

Deeply cutting into the grain is avoided as it weakens the wood and it is seldom necessary to remove more than one-sixteenth inch. Sharp, rapid cutting abrasives with light pressure do better work than dull abrasives with heavy pressure. Also in the latter case the soft wood between growths (grain) will be abrased quicker than the grain itself leaving hard ridges. For face work, sanding is done straight with the grain so as to avoid the danger of cutting deeply into the grain and leaving scratches. Sanding across the grain is mainly confined to mouldings and similar classes of work, much of which is, however, done by hand.

In some instances the surface is sponged with water and alum in order to raise and soften the grain and make the surface better suited for staining. Veneered stock should not be sanded inside two or three days after leaving the press and is thoroughly dried.

Garnet is the abrasive most in demand, but opinions differ as to the economic superiority of open-coated alumina papers since the latter are more expensive but usually last longer. Their special merits are dependent on the types of wood being sanded and the size of the grit used. For soft gumming woods which readily clog the paper, the cheaper flint abrasive is used. The special functions of these various abrasives have already been detailed in discussing their manufacture and uses.

The surfacing of wood work is mainly performed by means of machines onto parts of which the abrasive paper or cloth is fixed. These include drum, belt, disk, and spindle sanders. The drum sander consists of three or more cylinders covered with three or more grits of garnet paper or cloth from 2 down to ½. The endless abrasive belts are usually cloth of 1½ to 2/0 grits. The disk consists of a flat wooden wheel or disk, onto the sides of which the abrasive paper is glued. Spindles are comparatively small wooden cylinders and cones of varying diameter onto which the paper or cloth is glued and are used for surfacing concave curves, such as in furniture.

Although these machines are mainly applied to wood, they are also to some extent employed on metals, but in these instances artificial abrasives with cloth backing are used.

Leather Dressing

Leather and shoe dressing industries consume a considerable quantity of abrasives in the form of paper and cloth. The "working up" of the crude leather and the final preparation is entirely performed by means of abrasives. Numerous changes can be brought about in the finish of a piece of leather by the methods of handling and by varying the use of the abrasive.

Silicon carbide in fine grits is very popular, though there is a large demand for garnet. Approximately a million dollars worth of abrasive coated papers are used annually in the United States tannery and leather dressing industries. The fitting and shaping of the heels and soles of *boots and shoes* are entirely dependent on abrasive material, both garnet and silicon carbide paper and cloth being used. (Plate XV.)

Some felt hats are finished with "pouncing" paper, a term derived from "papier de ponce" when pumice coated papers were used 80 years ago. Very fine grit flint or quartz is now used, graded from 0 down to 12A (4A being about equal to 7/0 garnet).

BUFFING

Buffing consists of imparting a high lustre and finish to the surface of the work, either metallic or non-metallic. This is performed by means of a rapidly revolving soft flexible wheel, usually of muslin, on the face of which a soft abrasive is constantly applied and against which the work is held either mechanically, or more often by hand. There is very little abrasive action in true buffing or "colouring" as it is more in the nature of "burnishing" or smoothing down.

Buffing Materials

The abrasives in the great majority of instances are applied in the form of grease compounds, known as buffing compositions, which are divided into two general classes of "cutting", and "finishing" or "colouring" compositions. Both these are subdivided into (a) moulded compositions, which are a mixture of the abrasive with grease, and (b) powdered abrasives, which are used either dry, or more often with water only.

The Abrasives

The following materials, in order of their hardness, toughness, and sharpness are used for buffing. Emery, tripoli, pumice, flint, amorphous or soft silica, lime, some metallic oxides such as crocus, the various rouges (red, green, and black), and putty powder. Owing to the fine nature of their work, their accurate grading is a matter of extreme importance, as a single oversize grain might ruin the lustre being imparted. The abrasives must also possess the property of carrying or absorbing the grease binders used in the moulded compositions and to give them the property of adhering to the revolving face of the buff.

The cutting down abrasives are as follows:—

Emery. This mineral is fully described on pages 36 to 41 of Part II. It is the hardest of these abrasives and is only used in flour grades to a very limited extent for buffing, either in the form of a paste or cake for buffing iron, steel, rough brass castings, etc. It is more of a polishing than a buffing material and is thus used to a considerable extent when glued onto flexible wheels. Turkish emery is usually preferred.

Tripoli. This natural very fine-grained silica is mined in Missouri and Oklahoma and is by far the most important abrasive used in buffing. Details of this mineral will be found in Part I, pages 70 to 77. It is highly absorbent and works very rapidly on the softer metals. It is sometimes mixed with powdered quartz in order to increase its cutting action, but best results are obtained with the pure material.

Tripoli is an all-round buffing agent and one which is almost universally used. The grinding and grading of the powder previous to its use in compositions affect the quality of the finished product. Buffing tripoli is nearly always pink in colour. It is used on aluminium, brass, jewellery, silverware, etc., also on celluloid, pearl, etc.

Diatomite should not be confused with tripoli. It is a much softer silica composed of minute plant skeletons or diatoms. It is sometimes known in the buffing trade as "fossil" tripoli. It is not made into grease compounds owing largely to its excessive absorption. It is, however, employed in the lump or powdered form in the jewellery and lapidary trades. For full details see the writer's report.[1]

Pumice. American-ground Italian pumice, in the finest grades, is used mainly for the buffing of hard rubber and vulcanite mixtures; it is also sometimes employed to produce brass brush effects. Details concerning pumice will be found in Part I, pages 80 to 93.

Flint is rarely used for buffing except as an adulterant in some such materials as soft silica or tripoli. Its uses which are limited are mainly for tumbling work, cleaning off rust or grease from metal pieces, and for general scouring purposes.

The colouring or finishing abrasives are as follows:—

Soft Silica. This mineral is very similar in appearance to tripoli but is usually white in colour. It is often described as amorphous silica, it is, however, not amorphous but micro-crystalline and in the trade is referred to as "silica" when applied to buffing. For description see Part I, pages 70 to 77. It has a softer cutting action than tripoli and is an intermediate between the cutting and colouring abrasives. Its employment in buffing is considerably less than tripoli. It is, however, frequently used for cutlery, brass, copper, aluminium, engraver's copper plates, etc., but more particularly ivory, bone, piano keys, pearl, wood pipes, celluloid, etc. In some instances the soft silica is used to colour the above materials after a tripoli buffing, and in some forms is specially well suited for the colouring of brass and copper prior to plating.

Lime, or Vienna lime, originally came from Austria, but is now obtained from Wisconsin. It is an unhydrated dolomite containing a high percentage of magnesia. Details appertaining to the uses and theory of action of this

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[1] Eardley-Wilmot, V. L.: "Diatomite", Mines Branch, Dept. of Mines, Canada, Rept. No. 691 (1928).

material will be found in Part I, pages 96 to 98. It must be kept in a sealed container when not in immediate use, as it rapidly hydrates and loses its properties. It produces a high finish on nickel, brass, copper, bronze, and other metals as well as celluloid. It is, however, now the standard material for nickel, giving it that peculiar and desirable "under surface" blue known only to this metal. Lump lime is used in tumbling barrels for the final polishing of steel balls. Several compounds are made in which the other abrasives, such as silica and rouge, are mixed with the lime. Tests have shown, however, that a good pure lime compound gives higher lustre, as good a colour, and works as fast as a composition containing, for example, 8 to 10 per cent of silica.

METALLIC OXIDES

It has been proved that the highest lustre on metals is obtained by means of certain metallic oxides. Experienced polishers frequently state that "It takes a metal to polish a metal". Certain metals have a particular affinity for each other, so that when one of them is in the form of a polishing medium the best lustre will be produced on the surface of the other which is being polished.

Crocus, or crocus martis, is the hardest of these oxides. It is a purple-red, hydrated iron oxide. The grain is comparatively sharp and harsh. Of the two types: the American material is harder than the English, but the latter is a superior product and produces a finer finish. Crocus was until recently the standard buffer for obtaining a high polish on iron and steel surfaces, particularly that of cutlery; it is also used on tin and Britannia metal. It is sometimes used to impart a certain bluish colour to brass or copper, which cannot be obtained with tripoli, since the latter forces its way into the pores of the metal and spoils the colour. For this purpose a leather-faced wood wheel revolving at a low speed is used. Crocus is harder than lime and is about equal to soft silica. Its use is, however, declining as it is being replaced by the more superior green rouge and lime for steel and nickel colouring.

Rouge. The colour of buffing and polishing rouges, which are also oxides of iron, varies from a brownish red to a pale red, depending on the heat to which the ingredients are subjected during manufacture (*see* "Manufacture," page 101). The darker the colour the harder is the rouge. The grains of rouge are rounded and thus differ from crocus which is also considerably harder.

Rouges are amongst the earliest known of the buffing materials and owing to their extreme variation in hardness, uniform production is difficult. The rouges are the most universal buffing materials for the final polish on the precious metals, particularly gold and silver, and sometimes for brass and steel requiring the highest lustre; also for preparing metallurgical specimens for the microscope. Probably the largest individual use for rouge is in the powdered form with water for polishing plate glass.

The great variety in these rouges and some of their special applications have been tabulated by A. P. Munning and Company and is given later in part.

Black rouge (glassite) is a black magnetic iron oxide. It possesses a certain "drag" and is sometimes used on plate glass. Harder grades are made of this rouge, which are well adapted to the buffing of aluminium, silver plated reflectors and similar work. A hard, blue-black, "steel glossing" rouge is used for producing the highest lustre on steel parts such as watch movements and surgical instruments.

Green rouge, an oxide of chromium, is one of the oxides most recently used as a buffing medium. Its main use is for buffing platinum and steel, particularly "stainless" steels, upon the latter of which a higher lustre is imparted, if correctly applied, than with any other buffer. The finishing of the recently introduced chromium plating is performed with green rouge. In order to get the best results it is important that the work and the composition should be absolutely clean and free from any impurities such as other metallic oxides, sulphur, etc., otherwise certain changes in the surface will take place which will injure the appearance of the work. When pure, the chromium is believed to amalgamate with the steel upon which it forms a protective coating. This, however, must be brought about by a sufficient speed of the buffing wheel to create the necessary heat through friction. Chromium-finished products have almost revolutionized the cutlery industry.

Some green rouges, sold as such, are imitations, being the pale red rouge coloured green and naturally do not impart the desired finish. This can readily be detected by a simple test for iron.

Manganese dioxide is said to be a good polishing medium but is not much used because of the black dirt which is difficult to remove from the pores of the skin.

Satin rouge has a similar appearance to black rouge or manganese dioxide, but is much lighter a weight since it is composed largely of lampblack. It is occasionally used for work from which the minimum surface must be removed, such as certain types of thin silverware or plating, and for polishing the very thin plating used on coffins; also for polishing black or dark celluloid or bone materials. A somewhat different application consists of filling up a used emery-coated flexible wheel with charcoal or lamp black after which the face is rubbed down by hand stone until the wheel face becomes polished. This is then used to impart a high lustre on steel.

Putty powder. The best grade putty powders contain 85 to 90 per cent of tin oxide, the remainder being lead oxide. It is made by burning certain proportions of tin oxide and litharge in an electric furnace so that the ingredients combine. As pure tin oxide is fluffy and light and would wash away quickly, enough lead is added to give it a body. The polishing action is more one of filling than of abrasion, and it is the combination of filling with slight abrasion that imparts the high polish to granite and marble for which it is the standard and unequalled polishing medium.

Low-grade putty powder containing over 50 per cent lead oxide was at one time extensively used for glass polishing, also for machine polishing. Its use in this respect has rapidly declined owing mainly to its poisonous nature due to the lead.[1] The price of the powder is governed by the percentage of tin present.

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[1] The author wishes to correct the impression that all putty powders are poisonous as mentioned on page 98 art I.

TABLE X

Characteristics and Uses of Rouge[1]

HARD ROUGE

Characteristics	*Uses*
1. High-coloured and fine oxide.	High grade for silver watch-case work.
2. Light-coloured oxide not quite so fine as No. 1.	General jeweller's rouge. Same as above, but less expensive.
3. Brighter oxide, somewhat sharper than No. 2.	Jeweller's rouge. For use where an exceptionally high finish is not required.
4. Medium shade oxide.	An all-round rouge for flat and hollow silverware.
5. Medium shade, moderate cutting oxide.	A medium cutting rouge for flat and hollow silverware. Also suitable for colouring nickel or brass.
6. Medium shade. Slightly faster cutting than No. 5.	For flat and hollow silverware. Also for colouring silver novelties.
7. Dark shade oxide.	Very fast cutting with exceptional colouring qualities for flat and hollow silverware.
8. A carbon black with exceptional polishing qualities.	Silver plated reflectors, beaded and filigree work. Easy to wash out.
9. Medium shade, fine but fast cutting oxide.	Bedsteads, chandeliers, and brass and nickel colouring. General job shop use.
10. Bright shade and exceptional oxide.	The standard jeweller's gold rouge. Also for gold watch-case work.
11. Slightly darker than No. 10.	For cheap jewellery and high colouring of brass, previous to gold plating.
12. Black oxide, sharp cutting.	For platinum colouring.
13. Green oxide.	For obtaining highest colour on platinum.[2]

SOFT ROUGE—(POWDERED, LUMP, AND BALL)

14. Very bright soft oxide.	High colouring, dry buffing silver.
15. Somewhat darker oxide.	Same for gold.
16. Blue-black oxide very sharp. (Three grades of sharpness).	Steel parts of watch movements and surgical instruments (steel glossing).
Rouges—Watch Case—	
17. Very bright oxide in soft lumps.	Inside of watch cases.
18. Same as above in soft balls.	Same as above.
19. Same but in powdered form.	Same as above.
Rouges—Optical—	
20. Very bright oxide in soft lumps.	Fine lens polishing.
21. Same in ball form.	Same as above.
22. Same in powdered form.	Same as above, high-grade.
23. Darker oxide.	Less expensive than above.
24. Darker and sharp.	Cheapest grade.
Rouges—Glass	
25. Medium bright oxide in ball form.	Glass work—bevellers.
26. Same in powdered form.	Same as above.
27. Darker oxide.	Cheaper grade.
28. Darkest and sharpest oxide.	Cheapest grade.

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[1] A. P. Munning & Company, Matawan, N.J. Cat. No. 10, pp. 132–133 (1924). Trades numbers, symbols, and weights have been omitted and reference numbers substituted.

[2] Also stainless steel and chromium plate.

The following table links together the surface to be buffed or polished and the usual composition for cutting down or colouring.

TABLE XI

Uses of Cutting and Colouring Compositions

Surface	*Cutting Down*	*Colouring*
Aluminium	Tripoli	Silica
Bone	“	Black A rouge
Brass bed	“	Rouge
“ cast	Emery paste and tripoli	Lime, rouge
“ chandelier	Tripoli, old brass	Rouge
“ sheet	“	Lime, rouge
Celluloid	“	Lime, silica
Coffin hardware	“ crocus	Rouge
Copper engraver's sheets	Silica	Crocus, lime
Die castings	Emery paste, buffing tallow, tripoli	Lime
Fibre	Fibre cutting	Rubber finishing
German silver	Tripoli	Lime, rouge
Glass	Emery and pumice	Rouge
Gold	Tripoli	“
Hard rubber	Rubber cutting and pumice cutting	Rubber finishing
Ivory	Tripoli, silica	Lime
Jewellery	Tripoli composition	......
	Bobbing “	......
	Fossil powdered and lump tripoli	Rouge
Pearl	Tripoli lump and powdered lime	Lime
Platinum	Special platinum composition tripoli	Rouge
Steel	Emery paste, buffing tallow, tripoli	Lime
Steel balls	Lime	“
Syphon heads	Tripoli	Crocus
Tin sheet	Crocus	“
Wood	Tripoli	Silica

Grease Compositions

As previously stated the above detailed abrasives are generally mixed with certain greases and made up in some convenient form such as bricks or sticks.

The greases used in making these so-called "moulded" buffing compositions are stearic acid, mutton tallow, petrolatum, paraffin, and various animal and vegetable waxes. The stearic acid is a white fatty acid which is hard but not brittle and is made by the hydrolysis of tristearin contained in beef or mutton tallow, the best being from beef tallow by saponification. The mutton tallow is of the first quality open-kettle edible type. The petrolatum is a mineral oil or paraffin base product of the distillation of Pennsylvania mineral oil which has superior lubricating qualities and makes a good binder as it adheres well to the wheel without charring or glazing. It can be made more completely saponifiable by mixing with suitable animal greases. The paraffin wax is pure white, with a high melting and vaporization point and is distilled from the same Pennsylvania oil as the petrolatum just described. Beeswax was at one time used and is an exceptionally good material, but is now difficult to procure. The best products are now made with stearic acid and tallow, but are comparatively expensive.

There are three problems connected with the manufacture of buffing compositons: first, the hardness of the resultant mixture, which determines the permissible ratio of grease to abrasive; second, the control of the melting and vaporization points, the former of which determines the adherence of the composition to the face of the wheel, while the importance of the vaporization point is due to the fact that the composition sticks to the wheel at the temperatures only between the melting and vaporization points; third, the degree of saponification which depends on the ultimate treatment of the work after the buffing process, for example, if work has to be plated, the grease must be such that it is quickly and totally saponifiable in the cleaning solution.

The proportion and types of greases used also have a direct bearing on their buffing qualities; thus several different grades can be made with the same abrasive, known as "greasy", "medium", and "dry", and depend largely upon the proportion of grease to the abrasive. Heavy work, such as buffing nickel-plated steel, requires a greasy compound; while light work such as nickel-plated copper or brass calls for a dry compound.

The proper proportions, temperature control, and other details are closely guarded secrets of the manufacturers.

CHARACTERISTICS OF A GOOD BUFFING COMPOSITION

The finished cake must be sufficiently hard to avoid breaking and crumbling at ordinary temperatures. It must stick to the face of the wheel as long as the abrasive retains its cutting qualities and no longer; also the melting point should be correct so that the proper amount of material can be applied to the wheel and possess enough lubricating quality to avoid excessive heating. It should remove the defects from the surface to be buffed and the right amount should be used so that the work is done by the composition and not by the cloth wheel. It must not glaze the wheel nor accumulate hard particles. It should clean up the work well and not leave a noticeable deposit. "Smutting" is caused by too much composition being used and may be avoided by using a less greasy cake or by increasing the wheel speed. The composition must be of a nature to saponify readily and be easily soluble in a suitable cleaning solution so that the finish obtained by the buffing is not subsequently spoiled when the article is washed. Finally, it must be economical by producing a high ratio of finished parts per unit cost and must be accomplished with minimum wear and tear on the materials and machinery.

Greaseless Metal Finishing. Greaseless compositions are now often used on metals requiring "brush brass" or satin finishes. This finish has been employed for the last 20 years, but owing to trouble with the binders, unsatisfactory results were obtained. The binders were mainly glue and acetic acid which have too low a melting point and would often become too hard for practical use. This has now been overcome by using a rubber composition having a small amount of moisture[1] which may be retained by keeping the composition in metal foil containers.

It functions somewhat differently to the ordinary grease compounds in that when applied to the face of the wheel the binder dries rapidly due to the revolving wheel. This produces a quick-cutting, dry, abrasive-coated wheel with a flexible surface. New wheels are started with an extra heavy coating using about 2 inches of the cake, which is allowed to dry before being used.

The work to be finished by this method should be clean and free from all oil or grease which otherwise prevents the wheel from holding the greaseless compositions. Several types of wheels are employed according to the class and nature of the work to be finished. The usual type is an 8-inch loose muslin buff. Sewed buffs are used where considerable cutting down is required but are less flexible than the loose type. Felt wheels are used for the high parts of relief work and walrus hide for high polishing of steel. For very dull effects horse hair wheels are most suitable, but they have poor cutting qualities.

Greaseless compositions are at present suitable only for producing brushed or satin finishes and cannot be used for producing a high finish on soft metals, for which lubrication appears to be necessary.

Types of Buffs and Their Manufacture

The buff, known in England as the "mop" or "dolly", is a lightweight flexible wheel and as such has already been described under that heading when used for polishing. A few additional notes applying directly to buffing are hereby given.

It is now recognized that only the best and uniform grade material must be used and not old scraps and discarded material. The principal type consists of variations of cotton cloths. In the cotton industry the lengthwise threads are called the "warp", and the cross threads the filling or "weft". Specifications are based on the number of threads per inch in both these, as well as the width of the goods and the weight per running yard. It is found that cotton sheeting or shirtings of good weight and body, averaging about 68 x 64 threads per square inch, were the most suitable for the manufacture of buffing wheels.[2]

There are three distinct types of buffing wheels: first, the "*loose*" buff made up of full disks stitched in sections with a single row of sewing around the arbor hole; second, "*full disk*" sewed buffs which are spirally or concentrically sewed (about ¼ inch apart) over the entire surface between the hole and the periphery, which gives it greater stiffness and resistance to bending when in contact with the work; third, "*pieced-sewed*" buffs made of pieces too small to be cut into disks and sewed spirally as in the second type.

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[1] Leather, R. S.: "Greaseless Metal Finishing Compositions." The Metal Industry, pp. 59-60 (July 22, 1927).
[2] Divine, B. H.: "The Manufacture of Buffing Wheels," Machinery (July 1923).

The spiral or concentric sewing is accomplished by an automatically controlled two-needle machine which operates at the rate of 1,000 stitches per minute. The perfection of this machine can only be realized after endeavouring to drive a wire nail through a $\frac{3}{8}$-inch buff. Since a buff revolves sometimes at 12,000 s.f.p.m., the question of balance is a highly important one, so that the greatest care must be exercised in the manufacture of "pieced-sewed" buffs. This type of buff is sometimes provided with several cardboard disks between sections known as a "Bias" buff. Other forms of buffs include the hand-sewn *woollen* buffs made from woollen cloth; these are used at low speeds where the minimum amount of material must be removed and are thus wholly used on the precious metals. Hand-sewn *Canton flannel* buffs are used for silverware. These hand-sewn wheels are made up in layers 18 to 20 to the section and sufficient sections to form a 1- to 3-inch thick wheel. The entire wheel is then punched through with concentric holes and sewed by hand. When the wheel wears down to the first row of sewing, that row being independent of the next row, can be taken out without opening up the buff. Jeweller's buffs are hardened at their centres with shellac or glue to permit the use of small tap or screw spindles. Soft and flexible *sheepskin* buffs are used for certain classes of work; also *solid felt* wheels which are well suited for surface buffing relief work leaving the recessed surface in the original frosted condition. These wheels are also often used for polishing aluminium.

Brushes. These include the *brass brush* used with soap and water to clean silver after it has been plated. It is also sometimes employed to give a dull or frosted effect to brass. Steel brushes are used for aluminium frosting.

Cornstalk and *Tampico grass* brushes, in the form of buffing wheels, are used with pumice powder on bone, ivory, and celluloid ware.

Cleaning of Buffs.

Buffs are kept clean by constantly applying a "buff stick" to the wheel face. This is made from a lath of wood, 2 x 1 x 18 inches long, coated with glue up to the handle, dried, rubbed down with pumice, and again coated with glue, after which it is set up with alumina grit. This latter procedure is repeated several times until a good head is formed.

Wheel Speeds and Methods of Buffing

The peripheral speed of a buffing wheel is highly important. This naturally varies according to the nature of the work, type of wheel, and abrasive used, but the limits are between 6,500 and 10,500 s.f.p.m. If speed is too low the work tears the abrasive from the wheel in lumps and leaves smears on the work. Too high a speed causes "burning" of the work and destroys the wheel. Only a small amount of the composition should be applied at a time, and pressure should be applied lightly as too much results in an excess of the abrasive and grease, the latter "smutting" the work and retarding action. Separate wheels should be used for cutting down and for colouring; the latter requiring higher peripheral speeds than the former. After the work is finished the composition must be immediately washed off the parts by means of suitable solvents.

CROCUS AND ROUGE MANUFACTURE

Since these materials, which have already been described, are essentially used for polishing and buffing, an outline of their manufacture is given here.

Blue copperas or ferrous sulphate ($Fe\ SO_4$) is finely crushed and the powder charged into crucibles or in some instances into calcining furnaces holding about one-half ton. It is then heated for about 6 hours at 1,800°F. when iron oxide is formed. If various grades are required from the same furnace the contents are not stirred. The centre is a light-coloured, soft rouge called "Red Indian" rouge which is formed at 1,400°F. Towards the edges a darker-coloured and harder rouge is formed, while crocus is formed at the bottom. Usually, however, these are made separately in different crucibles, or furnaces, and the contents are accordingly well stirred in order to obtain an even grading throughout. The iron oxide is then raked out and dumped into washing vats where it is well washed with cold water and agitated for 24 hours after which the water is decanted off. The sludge is then placed in pickling vats where a solution of sulphuric acid is added, agitated, and after washing is allowed to drain, and then dried in some type of drier which will drive off the acid. For use on glass surfacing the sludge is sometimes mixed with ferrous sulphate solution to the right consistency for application as the rouge polish.

Special buffing rouges are produced by the distillation of ferrous sulphate and then heat treating the distillate after it has been evaporated into the pure sulphate crystals. By careful control of the temperature and the length of time that the heat is applied, various degrees of hardness and colour are obtained. The residue obtained from the manufacture of Nordhausen sulphuric acid is generally used by English manufacturers as the base of the crude ferrous sulphate.

Crocus is made in England by grinding and levigating and water settling pure varieties of natural ferric oxide. The American crocus is not made from the ferrous salt but by calcining iron pyrites or by treating the sulphuric acid plant residues.

Black rouge or the magnetic oxide is made by chemically precipitating ferrous sulphate with an alkali such as caustic soda.

Green rouge is made by calcining a chromium salt (hydroxide) at a high enough temperature to form an acid insoluble compound, and then precipitating a solution of the calcine with an alkali such as sodium sulphate. The precipitate is then well washed and dried.

LAPPING

"Lapping" refers to precision operations performed with metal laps, either plane or cylindrical, charged with a finely powdered abrasive either dry or lubricated with oil. The original operations are many centuries old and the name is derived from "lapidary", i.e. cutting precious stones by abrasive action. Emery, corundum, and both artificial abrasives are used. Emery is slow in action but imparts the highest finish; both corundum and the aluminous abrasive cut fast and leave a good finish, while silicon carbide cuts the fastest. The abrasive must be clean and uniform and on account of the irregularity of the natural material, a specially prepared silicon carbide grain has recently been put on the market.[1]

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[1] Willis, H. J.: "Uniform Abrasive Necessary for Gear Lapping", Ab. Ind., p. 19. (Jan. 1929).

The laps used for plane lapping are copper, tin, or cast iron, but in many instances, such as for vertically operated laps, they have a Babbitt or a lead and tin composition rim. The new lap is charged by rolling in the abrasive with the addition of oil by means of a small roller. Excess of abrasive should be avoided for uniform results and not more than 25 per cent in the vehicle (olive oil). The work after lapping should be thoroughly cleaned of all traces of abrasive.

Diamond laps are extensively used on small holes that cannot be ground. They generally consist of soft steel pins charged with diamond dust which is rolled into the lap and are run at high speeds.

TUMBLING

Tumbling barrels are now often used for grinding, polishing, or "burnishing" a number of small parts that are turned, stamped, or cast, such as balls, etc.

The materials to be finished are placed in an iron tumbling barrel with alumina grain and water, in the proportion of one pound of abrasive to one pint of water, after which the barrel is revolved for three or four hours. The abrasive and fines are then washed out and replaced by rottenstone or pumice powder and water in the same proportions as above and revolved for about two hours. The parts are then removed from the barrel, washed, and transferred to a wooden barrel with double their weight of steel burnishing balls. A solution consisting of one part of molasses to four parts of water, which has been allowed to age for several days, is added to the barrel and diluted with twenty parts of water. The contents of the barrel are then screened to remove burnishing balls and the solution, after which the parts are dried and plated. The colouring after plating is performed by repeating the burnishing operation in the wooden barrel which is revolved for fifteen minutes. The parts are then removed, screened, rinsed, and dried.[1]

SPECIAL GRINDING, POLISHING, AND BUFFING OPERATIONS

The details of grinding and polishing, both metallic and non-metallic, are beyond the scope of this report. The polishing of such metallics as aluminium, brass, bronze, silver, nickel, etc., and the operations performed by the trade such as in the automobile, cutlery, and numerous other industries call for specialized work.

A considerable quantity of abrasives is also used in the preparation of certain non-metallic raw materials which are almost entirely prepared by means of grinding and polishing. These are principally glass and stone, a very brief outline of the methods employed being hereby given.

Further details of these metallic and non-metallic grinding and polishing methods and industries can, however, be obtained through reference to the classified bibliography at the end of this report.

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[1] Schuldt, H.: "Grinding and Ball Burnishing"; Abrasive Industry, p. 19 (Jan. 1928).

Glass

The finishing of glass for the trade depends on its ultimate use or application and includes the grinding or surfacing, polishing and bevelling of the crude plate or mirror glass; glass cutting for ornamentation; the finishing of blow glass; and its preparation in the optical trade such as lens grinding and polishing.

Plate glass is surfaced and polished by means of a large number of flat circular polishers which individually rotate on the surface of the glass which is temporarily laid in a plaster-of-Paris bed. The operations consist of first surfacing by means of a number of grades of river sand; then "fining" with "flour" grades of various harder abrasives such as fused alumina, emery, or garnet; and finally polishing with rouge. The grading of garnet for this use is detailed in Part III of this series of abrasive reports.

There are at present no glass-surfacing plants in Canada.

Bevelling is performed by hand, the operator applying the edge of the glass to a flat, revolving iron disk onto which water and silicon carbide are allowed to flow; this is followed by applying the edge to a horizontally revolving, fine-grained natural sandstone, usually obtained from Newcastle, England. The next operation is with flour pumice on a poplar wood wheel and finally rouging on a cork wheel or wooden wheel covered with felt strips. For the automobile industry a number of sheets are bevelled simultaneously by passing them mechanically over a series of multiple grooved alumina wheels of varying grit.

Glass cutting is performed by first going over the sketched design with a series of thin, revolving steel disks, using silicon carbide with water as the abrasive, after which the rough cuts are smoothed with very fine-grained natural grindstones or aluminous wheels, a large variety of differently shaped wheels being required.

Optical Glass Grinding and Polishing. The carefully pressed blank lenses are placed in special pitch blocks or holders and automatically ground by cup or bowl-shaped grinders which rotate and reciprocate over the block (Plate XVIII). Silicon carbide and Turkish emery are used as the abrasive, though natural corundum (from South Africa) is now used for all stages by some of the largest optical concerns. The final polishing is performed with rouge.

Stone Surfacing and Polishing

The preparation of the rough blocks of granite for monumental and other ornamental work varies somewhat in different districts. The New England States are one of the principal fields on the American continent in which this work is done on a large scale.[1]

Large blocks of granite are cut by means of silicon carbide toothed circular saws, or slotted iron disk saws using chilled shot as the abrasive; while slabs are cut by means of band saws (*see* Part I, page 4). A number of blocks are placed in a bed of plaster-of-Paris and "ironed" by means

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[1] Simonds, H. A.: "Granite Polishing Industry in New England is Growing"; Abrasive Industry, p. 179 (July 1928).

of flat, iron disk wheels with chilled shot and water followed by silicon carbide and grit. The final polishing is performed by means of a horizontal movable arm buffer in conjunction with which putty powder (tin oxide) is generally used.

Preparation of Polished Ore Sections

The grinding and polishing of rock sections calls for very accurate work and being outside the category of the trade, a detailed outline of two sequences of operations is hereby given.

A.[1] *Order of Grinding and Materials Used*

1. Grinding flat surface with 120 silicon carbide on hard ores or F carbide on softer ores.
2. Section mounted on brass tube and ground with F silicon carbide. The corners are bevelled on a carbide wheel.
3. Grinding with special emery (B and L optical emery No. 906) for 30 seconds.
4. Rough polish on 60-ounce, canvas-covered lap with 600 silicon carbide—for hard ores only.
5. Polish on muslin-covered lap with "10 minute" silicon carbide flour for 3 minutes.
6. Polish on muslin-covered lap with water-floated chromium oxide or jeweller's rouge.
7. Polish on billiard cloth with finely powdered magnesium oxide or with black (magnetic) rouge.

B. By this system[2] the specimens are ready for the microscope within ten minutes.

Order of Grinding and Materials Used

1. A one-inch diameter specimen is ground in a horizontal plate using 46 or 120 aluminous or carbide grit. Bevel with carbide wheel.
2. Place specimen on plate glass mounted on a horizontal disk and grind by hand with 5 F aluminous flour.
3. Repeat with 60-minute alumina for about 1 minute.
4. Polish with a Norton polisher consisting of steel wheels upon which sheeting is stretched and revolve at 1,800 r.p.m. The abrasives are applied by means of a paint brush as separate operations in the following order:—(a) 60-minute alumina, (b) chromium oxide, (c) black rouge or shamva metallographic powder[3] for the final polish.

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[1] Short, M. N.: "The Preparation of Polished Ore Sections"; Econ. Geol., vol. XXI, No. 7, pp. 648-664 (Nov. 1926).

[2] Schwartz, G. M.: (Minnesota University), "Preparation of Polished Sections of Ores"; Econ. Geol., vol. XXII, No. 2, pp. 193-197 (March-April 1927).

[3] "Shamva" is a special magnesium oxide.

METALLIC ABRASIVES

Under the heading of metallic abrasives are included crushed steel, steel shot, angular steel grit, and steel wool. The process of manufacture of steel shot was invented about 70 years ago in Philadelphia. Shot was later made in Scotland from scrap iron and shipped to the United States. Twenty years ago there was less than 200 tons annually produced in the United States, but now one producer alone ships over 7,000 tons; the total annual output of metallic abrasives since 1917 will be found in Table III. There are at present no firms producing these products in Canada.

STEEL SHOT AND GRIT

Shot

Manufacture. Steel shot is chilled cast iron. The metals entering into the composition, such as selected steel scrap, charcoal, and iron, are smelted in a cupola from which they are continuously discharged over a period of eight to nine hours in several small streams. The streams of molten metal are subjected to heated air and steam pressure of about 80 pounds which divides the metal into spherical particles of varying size, and blows them into a water tank in which they are chilled. The tank is then drained and the contents are mechanically conveyed to a drying-room. The shot, made brittle by the rapid cooling, is heated in an oil-fired furnace from which the hot shot drops into a 100-ton bin where it cools gradually for 48 hours. During the heating and slow cooling the shot loses its brittleness and becomes tough and hard. It is then graded by screening into about 15 sizes ranging from 4 to 90 mesh. A careful standardization of sizes is rigidly adhered to by the larger manufacturers and the products are continually tested for hardness; a No. 10 shot, for example, should withstand a pressure of 1,000 pounds without crumbling.

Uses. The finer sizes of steel shot are extensively used in metal blasting equipment for the cleaning of castings, forgings, and heat-treated small parts; while the coarser material (15 mesh and over) is employed in connexion with the sawing, grinding, and polishing of stone, marble, and granite, also in core drilling and for making burnishing pebbles.

Steel Grit

Manufacture. Steel grit or crushed steel is made from high carbon steel and crucible sheet steel which are specially treated to render them brittle. The steel is then crushed by a specially designed equipment after which the crushed material is heat-treated to harden it and is then screened into 25 sizes from 20 to 200 mesh.

Uses. The sizes coarser than 90 are used for the sawing of stone, marble, onyx, and similar materials, also sometimes in the grinding of optical lenses (finer sizes only). The finer sizes are also utilized as one of the ingredients in steel cement and is particularly in demand by locomotive builders for facing surfaces together such as air and pipe joints, throttle valves, etc.

Angular Steel Grit

Manufacture. The 4-mesh shot material from the previously described operation is crushed in a ball mill and graded into about 15 sizes from 7 to 100 mesh thereby producing the crushed steel grit, "diamond" grit, or angular grit of the trade. A good grit should contain less than one per cent rounded particles; this can be tested by allowing some of the material to roll down an inclined board.

Uses. The main application of angular grit is in air blasting for cleaning castings of all kinds including grey and malleable iron, steel, brass and bronze, aluminium, drop forgings, and other heat-treated parts.[1] Grit is somewhat more effective than shot, particularly for cleaning castings and forgings, though in some instances the smaller sizes of steel shot are equally good and are cheaper.

During the blasting of castings the shot or grit becomes mixed with sand which is now separated out by a pneumatic air blast machine fitted with baffles causing the heavy metallics to drop, and the dust and lighter materials, independent of size, to be carried away.

The blasting operator often has to wear special protection equipment such as sand blast helmets fitted with a compressed air tube, metal lined gloves, etc.

Advantages of Steel Abrasives for Foundry Blasting

Some of the advantages claimed for the metal abrasives over sand are: the elimination of sand in crevices and corners; greater variation in sizes; considerable reduction of dust, due to the fact that the metal wears, while the sand pulverizes; with careful reclaiming they can be used from 200 to 300 times, while sand can be used only from 1 to 3 times[2]; reduction in storage capacity; handling costs reduced owing to the greater bulk of the sand; elimination of thawing problems in cold climates; and sandblast equipment requires no changes in order to use steel abrasives.

STEEL WOOL

Steel wool or "steel shaving" consists of long silky fibres shaved from steel which when massed together have the appearance of "wool."

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[1] Private Information, Globe Steel Abrasive Co., Mansfield, O.

[2] "15 Facts for the Foundry and Forge Shop", pamphlet issued by The American Steel Abrasive Co., Galion, O.

Historical

This product is said to have originated in Germany about 35 years ago when metal shavings were tried out to remove paint from some old pieces of furniture. These, however, being a waste product from the lathe broke down and did not last long, consequently the idea of using long thin strands of metal was conceived. For this purpose the by-product from the manufacture of loom-heddles was found to be a considerable improvement, but later a specially designed machine was invented by means of which wire was drawn under knives. The product from this operation found favour in the wood-working trade both for removing paint and as a substitute for sand paper.

Prior to the war, steel wool was largely imported from Switzerland and Germany, but now it is made by eight manufacturers in the United States whose total annual output is over 3,000 tons.[1]

The modern steel wool is of polygonal cross-section, usually triangular, but always possessing three or more sharp edges.

Manufacture

Steel wool is now made in nine regular grades from high-manganese (0·50 to 1·00 per cent Mn) Bessemer, basic or acid open-hearth, steel wire. Several types of machines are used. In the "shaving-block" machine the wire is dragged over a track and is shaved in the process by a number of inclined knife edges. Some types have a number of parallel shaving blocks over which multiple strands of the same single wire are drawn. In a more recent type of machine the wool is produced by drawing the wire through circular cutting dies. The Brillo-Field machine consists of a number of wheels (or power-driven cutting beds) in tandem, wire-supplying apparatus, and attachments for removing scrap wire and shavings from the wheels. Cutting is accomplished by means of serrated knives, the number of serrations varying from 10 to 250 to the inch according to the size and type of fibre (grades) being made. Over a mile of wire is run under the knives before it is reversed and rewound on the coil. In the coarser grades individual fibres have been made over 100,000 feet long. Improvements in manufacturing machinery have progressed to such an extent that now one machine can replace seventy of those used eight years ago, and the labour involved is reduced to about one-tenth. Details of the various processes and machines used will be found in a paper by Crosby Field of the Brillo Manufacturing Co.[2]

In Europe the wool is made by first shaving a thin fibre from soft steel wire in order to present a flat surface. The wire is then stretched over a frame beneath the cutting tool so that the wire is shaved with triangular-shaped threads.

Nine grades of wool are manufactured designated as follows: coarse, medium, and fine shavings which range from 0·008 to 0·001 inch in diameter, also regular grades Nos. 3, 2, 1, 0, 00, and 000; No. 3 being about 0·006 inch and No. 000, about 0·001 or less inch in diameter.

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[1] Field, C.: "The Steel Wool Industry"; Mechanical Engineering (Dec. 1927).

[2] Annual Meeting of the American Society of Mechanical Engineers, New York, Dec. 5 to 8, 1927. *See* Mechanical Engineering, Dec. 1927.

Uses

Steel wool was primarily used to remove paint from woodwork, the demand being still large for all painted or varnished surfaces for which No. 3 or fine shavings are the most suitable grades. It is a strong competitor of abrasive papers in the wood-working industry and some furniture manufacturers claim that by the use of the finer grades of steel wool woodwork can be finished faster and just as efficiently as with sand paper. It is used to put a "sun-burst" finish on aluminium ware. It is also used in the place of abrasive papers for cleaning hollow ware patterns, tools, sign plates, machine parts, enamelled ware, and numerous other articles. It finds a very extensive use in the household for scouring cooking utensils, sinks, etc. Fresh paint will not properly adhere to old varnished surfaces, but if previously rubbed over with steel wool, enough to dull the glaze, the paint will remain on for a considerable period and the wool is thus invaluable to the amateur interior house painter. In japanning work any drips, runs, or other defects are smoothed out by steel wool thereby eliminating any scratches that might have been visible after the second dip.

One of the main advantages of steel wool over abrasive papers is that the wool does not clog. Its disadvantages are that minute slivers penetrate the hands of the operator; also unless the rubbed surface is carefully cleaned the metal particles are liable to leave rust streaks. Besides being used for abrasive purposes, steel wool has recently been introduced into knitted cloth as a substitute for cotton padding in laundry pressing machines; it is also used as a furnace dust catcher.

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Carborundum Co.: "Carborundum Products for the Glass Trade," 27 pages.

POLISHING AND BUFFING TRADE

Divine Bros.: "Buffing Wheels," 25 pages; "Abrasive Metal Finishing Equipment" (Gives excellent descriptions of buffing wheels, their uses, buffing compositions and proper use of glue), 119 pages; "Standardized Abrasive Finishing Processes," 13 pages.

F. B. Stevens: "Buffing Compositions" (Gives compositions and the proper application of materials), 240 pages.

A. P. Munning Co.: "Cat. No. 10 (Gives details of various buffs, compositions, and uses) 275 pages.

Walter C. Gold Co.: 'Polishing Materials," 37 pages; also various small pamphlets on 'Buffs and Materials.'

Norton Co.: "Metal Polishing," 27 pages.

METALLIC ABRASIVE TRADE

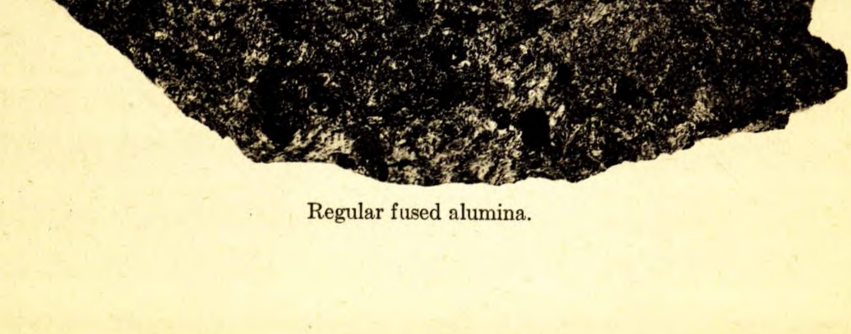
American Steel Abrasive Co.: Booklet on "Uses and Testing of Steel Shot."

T. H. Rhodes Co.: "The Story of Steel Wool," 9 pages.

Walter C. Gold Co.: "Steel Abrasives for Stone and Sand Blasting," 9 pages.

PLATE II

Typical silicon carbide.

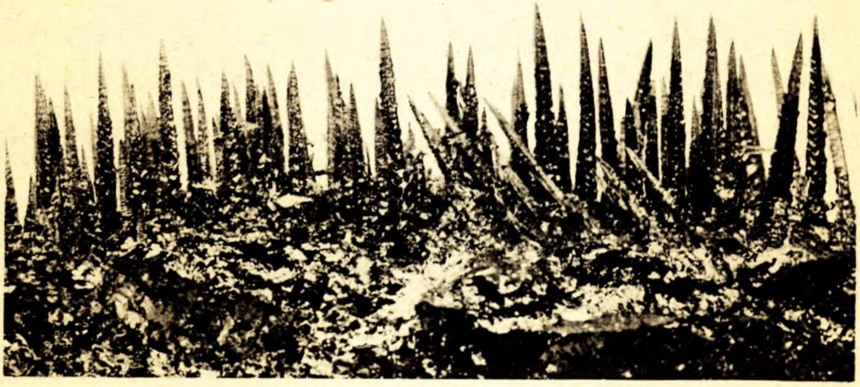


Regular fused alumina.

A. Special fused alumina made from amorphous alumina.

B. Special fused alumina made from natural corundum.

Highly developed silicon carbide crystals



Fused alumina crystals. (Magnified, 4 diam.)

PLATE V

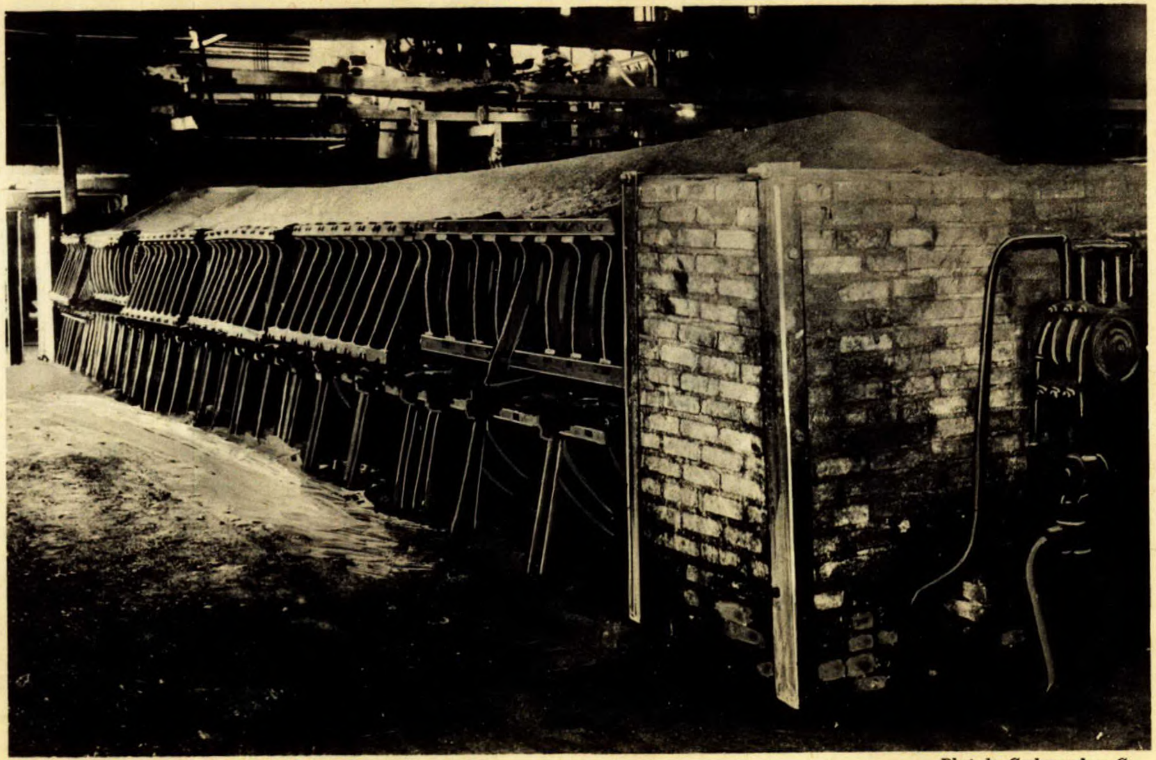


Photo by Carborundum Co.

Silicon carbide furnace loaded and ready to burn, showing electrodes and construction of removable sides.

PLATE VI

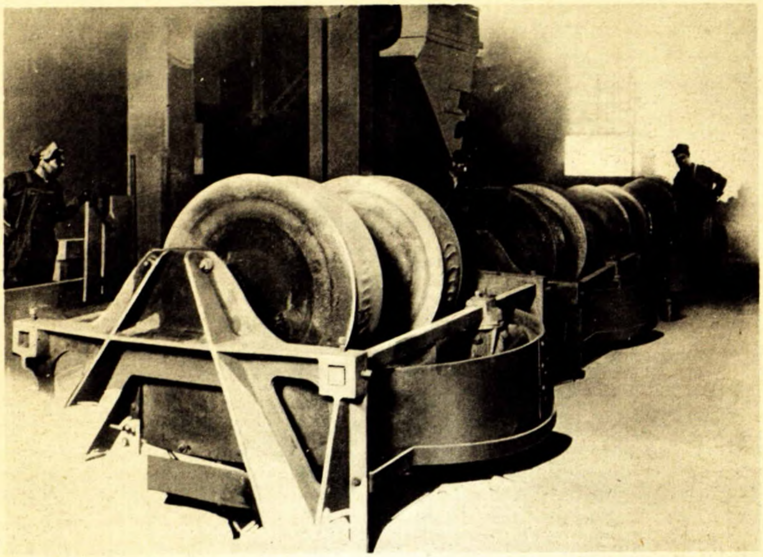


Photo by Carborundum Co.

A. Pan mill used for crushing crude silicon carbide.

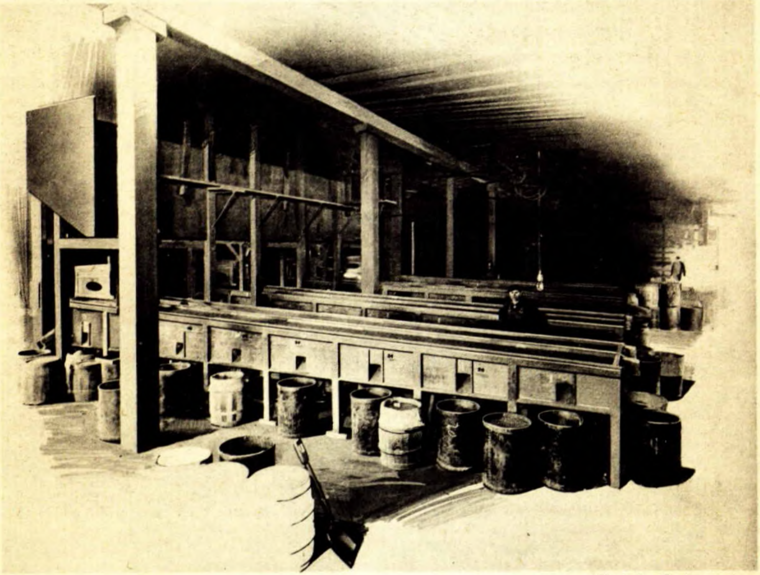


Photo by Carborundum Co.

B. Grading abrasive grains by screening.

Photo by Carborundum Co.

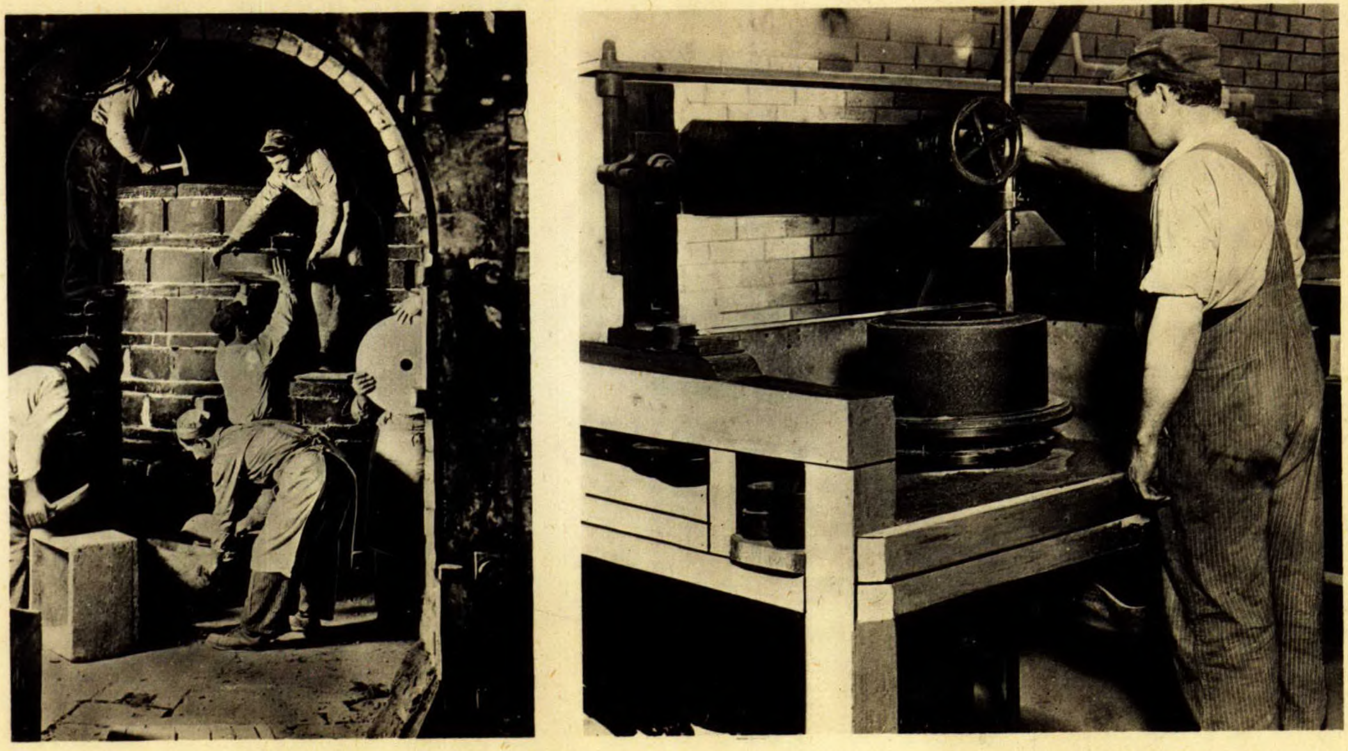
Fused alumina furnace (Hutchins type) in operation.

PLATE VIII

Photo by Carborundum Co

Grinding wheel manufacture—Vitrified puddled process: mixing kettles (left), and wheel ring-moulds with "batts" (right).

PLATE IX



A

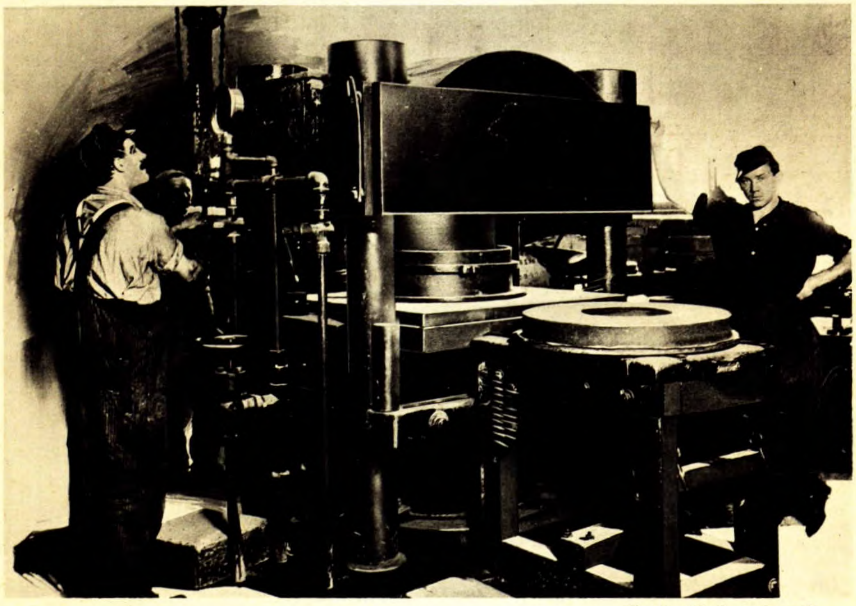
B

Photo by Carborundum Co.

Grinding wheel manufacture—Vitrified process: A. Loading large wheels into kiln, showing sectional "saggers." B. "Shaving" cylinder wheel blanks.

Courtesy Norton Co.

A. General view of a wheel grading (right) and inspection (left) department.



Courtesy Carborundum Co.

B. Hydraulic machine for moulding and pressing wheels made by elastic process.

PLATE XI

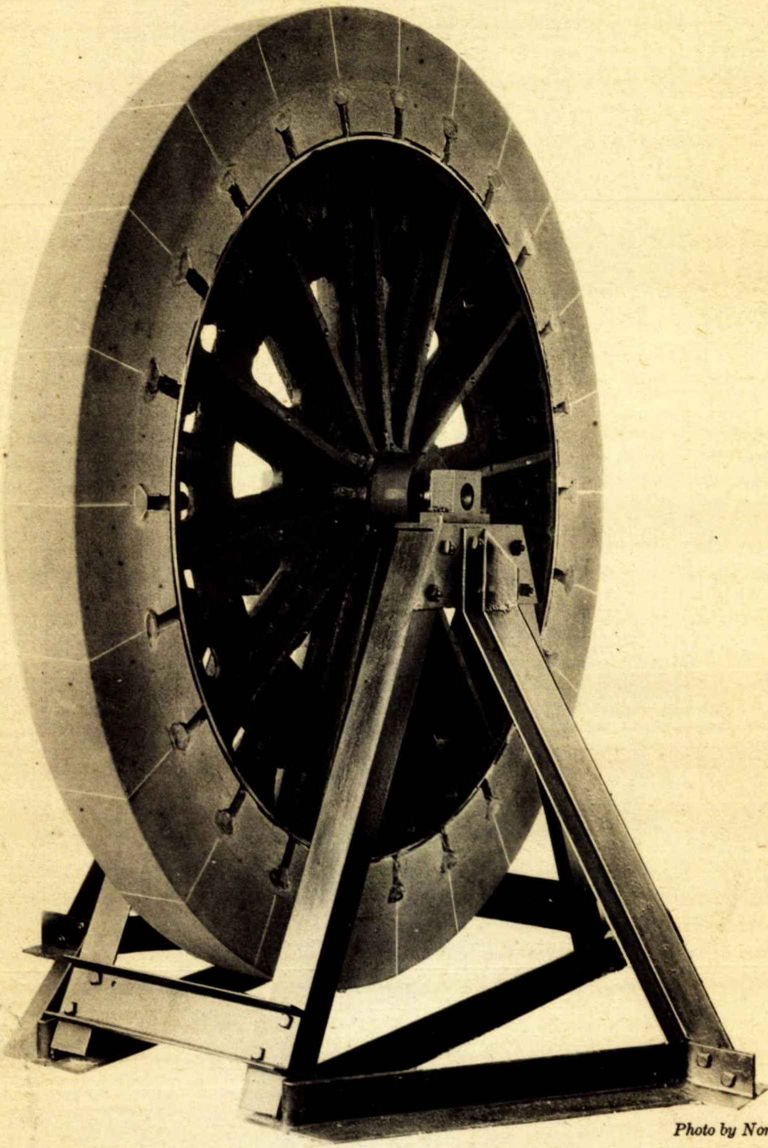


Photo by Norton Co.

A 72- by 6-inch grinding wheel

PLATE XII

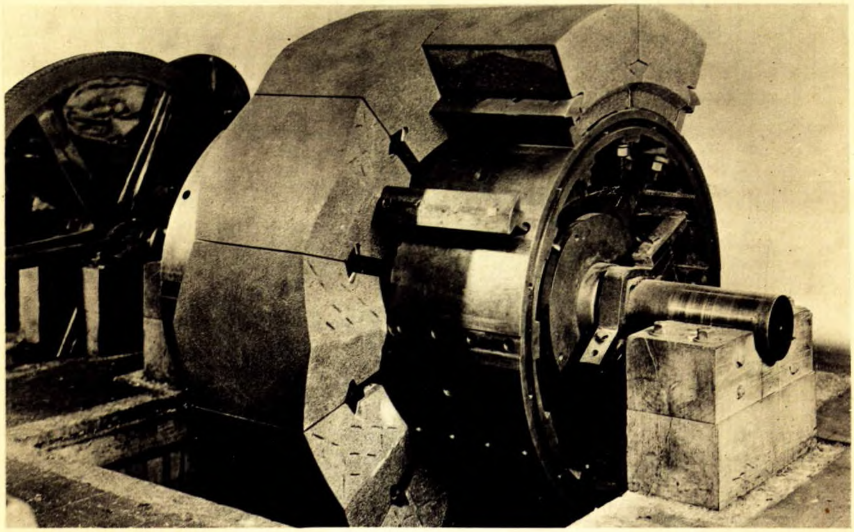


Photo by Norton Co.

A. Artificial pulpstone showing segmental construction.

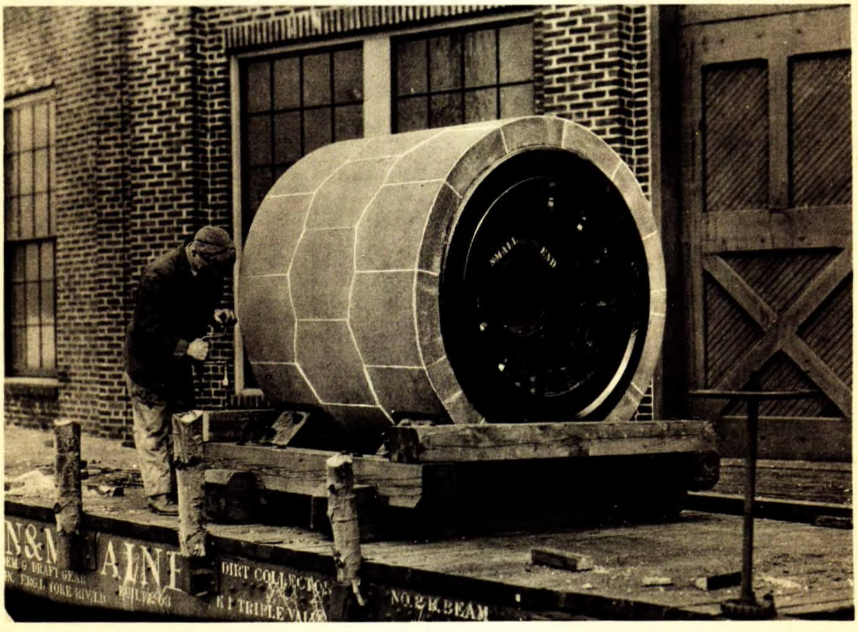
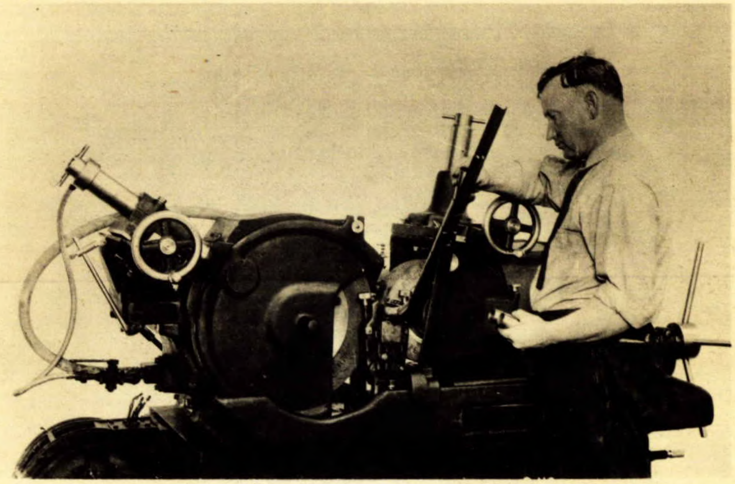


Photo by Norton Co.

B. A finished, 62- by 54-inch pulpstone.

PLATE XIII



A. Centreless grinding machine.

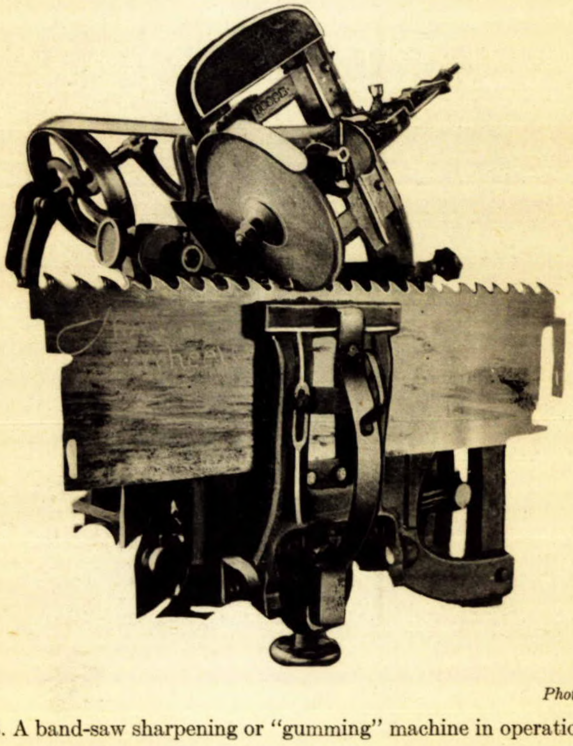


Photo by Norton Co.

B. A band-saw sharpening or "gumming" machine in operation.

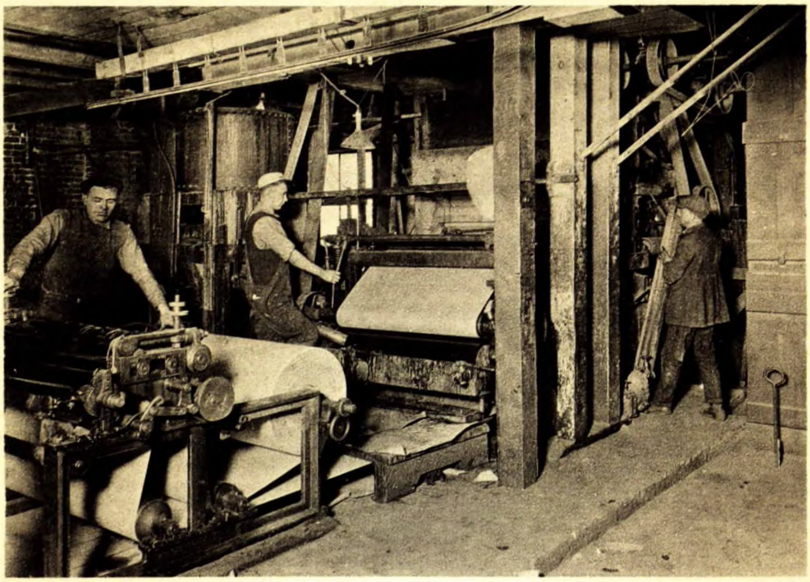


Photo by Baeder-Adamson Co.

A. Abrasive coated paper manufacture: The "making" machine showing paper roll; printing machine; glue trough, also abrasive grit feed hopper in right background.

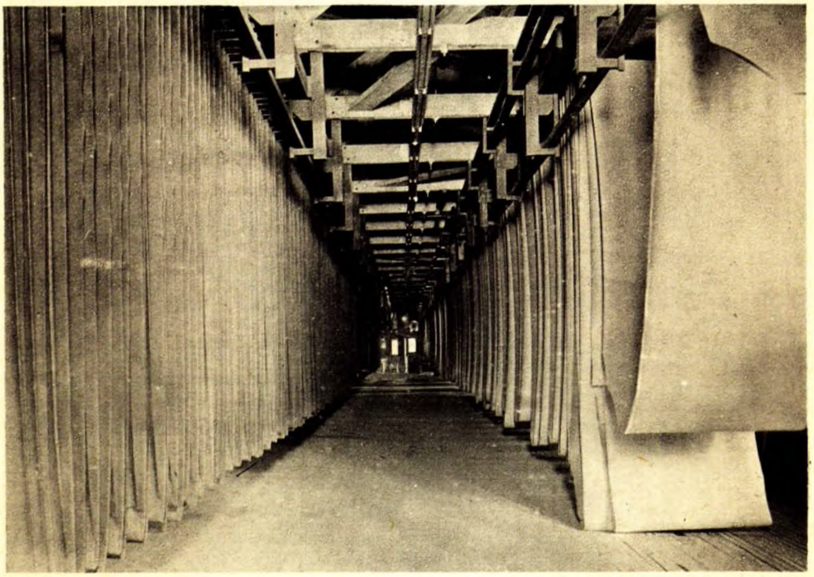
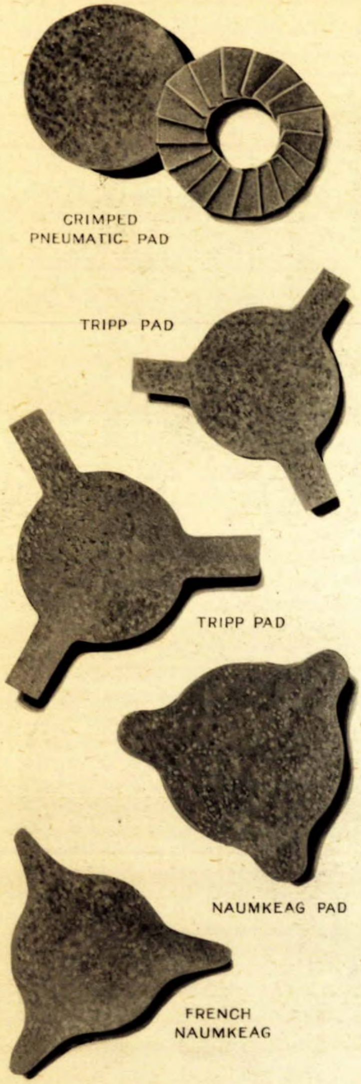


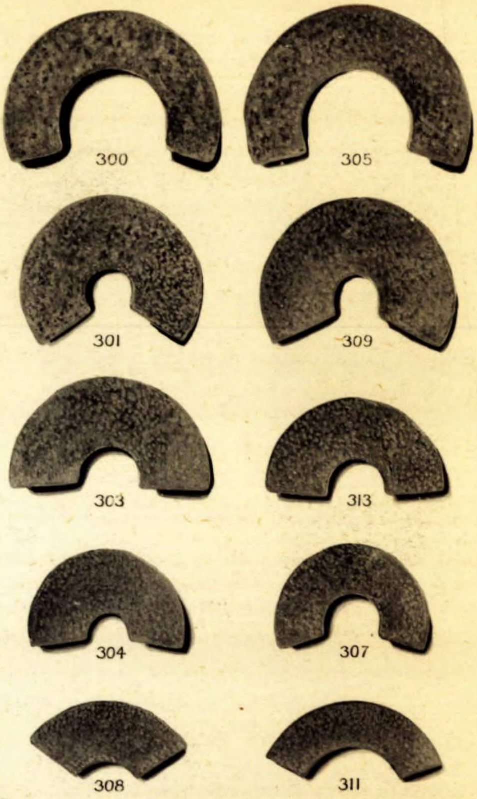
Photo by Baeder-Adamson Co.

B. Drying after sizing showing festoons on the travelling racks.

PLATE XV



SILICON CARBIDE CLOTH PADS

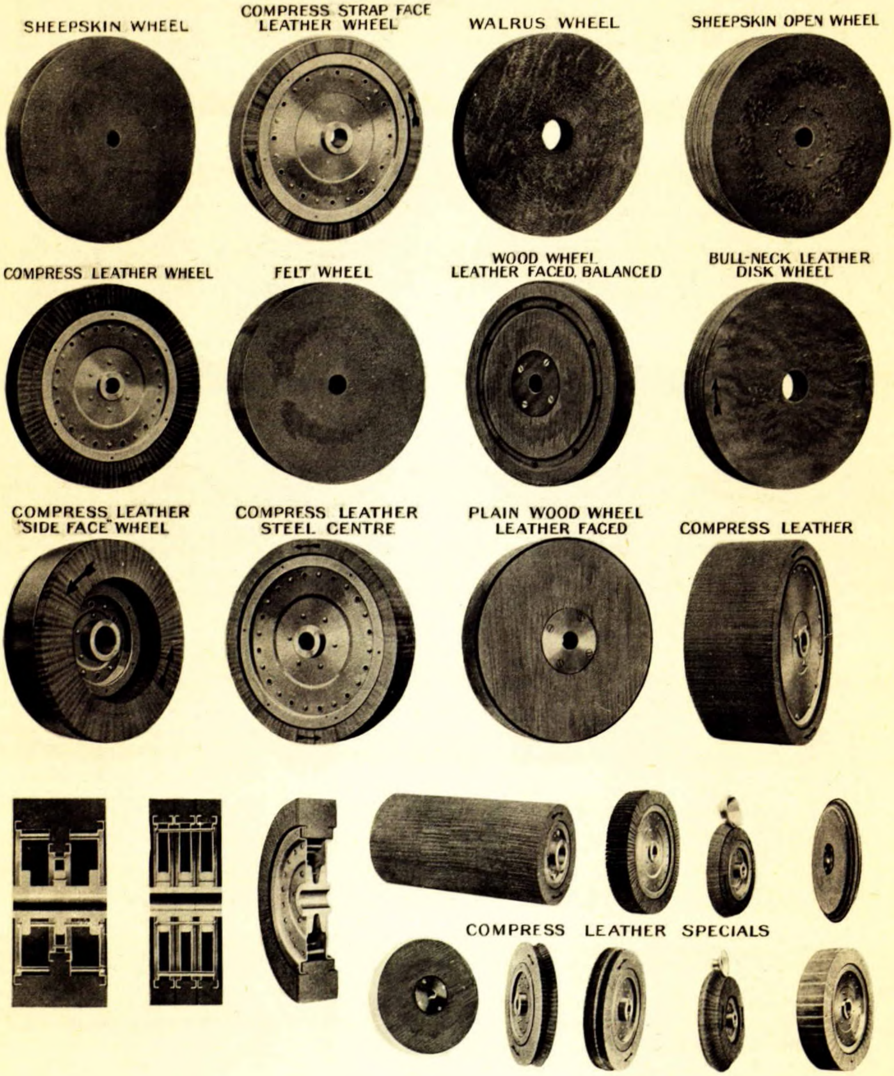


SILICON CARBIDE PAPER HEEL BREASTERS AND CONES

SILICON CARBIDE PAPER EMERSON CONE

SILICON CARBIDE PAPER OR CLOTH MOULDED SHAPES FOR HEEL SCOURING

PLATE XVI



SHEEPSKIN WHEEL

COMPRESS STRAP FACE LEATHER WHEEL

WALRUS WHEEL

SHEEPSKIN OPEN WHEEL

COMPRESS LEATHER WHEEL

FELT WHEEL

WOOD WHEEL LEATHER FACED, BALANCED

BULL-NECK LEATHER DISK WHEEL

COMPRESS LEATHER "SIDE FACE" WHEEL

COMPRESS LEATHER STEEL CENTRE

PLAIN WOOD WHEEL LEATHER FACED

COMPRESS LEATHER

COMPRESS LEATHER SPECIALS

VARIOUS DESIGNS OF FLEXIBLE WHEELS

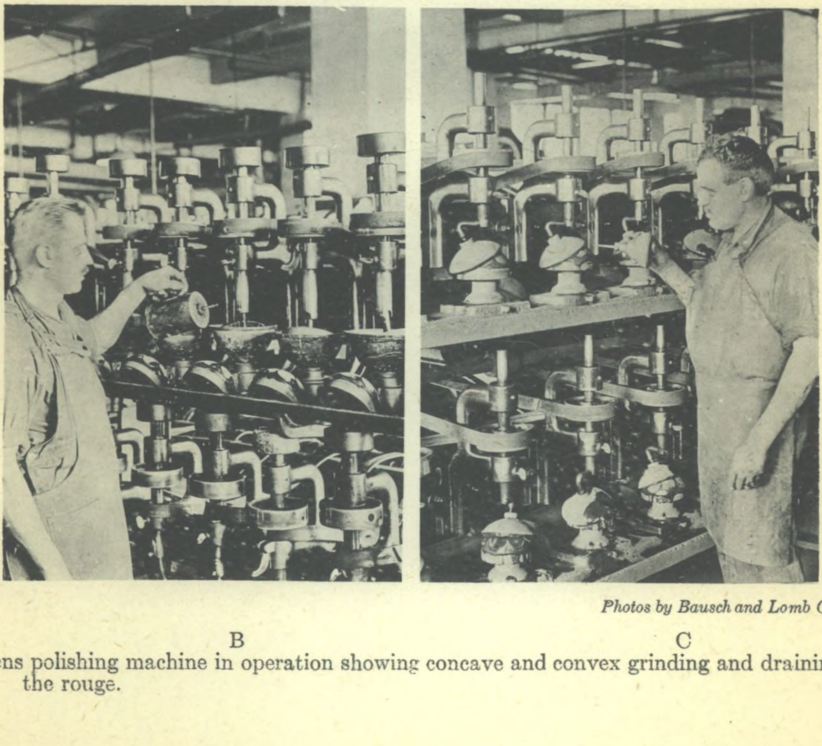
Plate XVII

Photo by Norton Co.

A well arranged setting-up room for flexible wheels.

PLATE XVIII

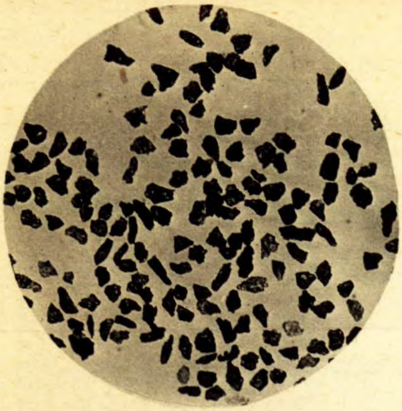
A
Lens grinding and polishing; preparing and blocking lenses.



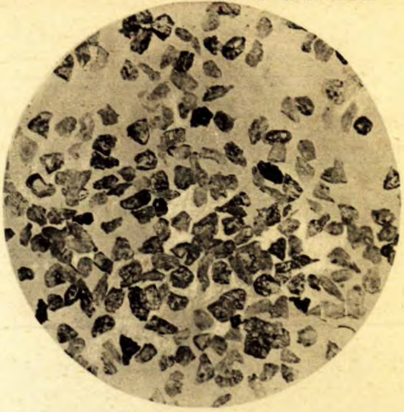
Photos by Bausch and Lomb Co.

B C
Lens polishing machine in operation showing concave and convex grinding and draining off the rouge.

PLATE XIX



A



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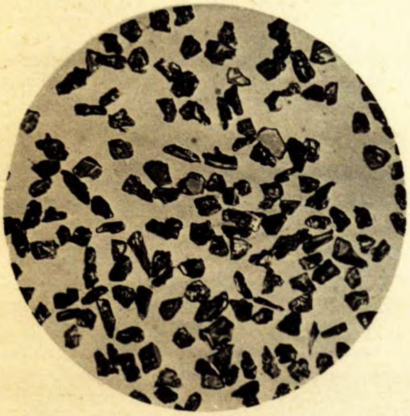

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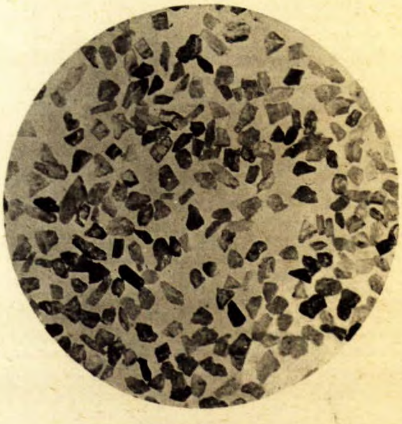

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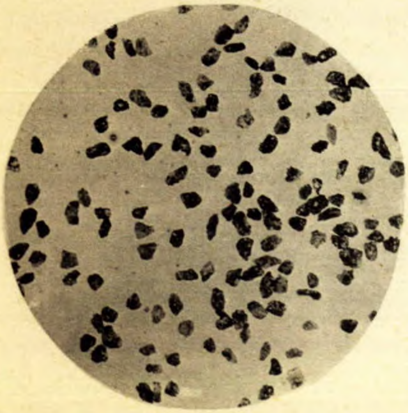
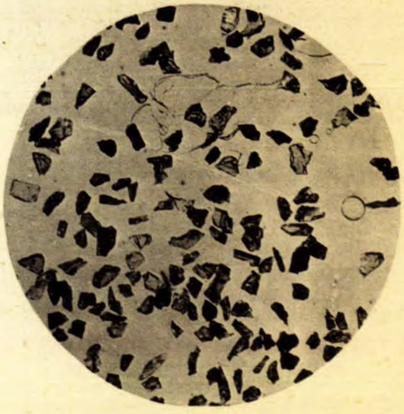


E



F

PLATE XIX

Photomicrographs of abrasive grains (36 to 56 grits: 5 to 7 magnifications)

A. Regular fused alumina.

B. Special fused alumina (made from natural corundum).

C. Silicon carbide.

D. Natural corundum (South Africa).

E. Natural American emery.

F. Natural garnet (North River, N.Y.)

INDEX