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THE EFFECT OF DIFFERENT SURFACE TREATMENTS ON THE FATIGUE STRENGTH OF DRILL STEEL

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The Effect of Different Surface Treatments on the Fatigue Strength of Drill Steel*

By T. W. WLODEK †

ABSTRACT

In this paper the relative merits of shot peening, induction surface hardening, spiral-rolling, and the combination of these surface treatments, are evaluated on the basis of their capacity to increase the fatigue strength of drill steel.

The *S-N* relations for plain carbon steel (SAE 1080) and Ni-Cr-Mo drill steels in the as-rolled condition were determined previously, using the new Canadian method of testing drill steel introduced at the annual meeting of the Institute in Toronto in 1950 (19). *S-N* curves have now been determined by this method for these two drill steels in the following conditions: shot-peened and drawn, induction hardened, induction hardened and shot-peened, and spiral-rolled. (S.R.).

The ratios of the fatigue strengths of these steels after surface treatment, to their fatigue strengths in the as-rolled condition, are compared and the most beneficial treatments are thereby pointed out.

The expected range of stresses and their distribution during actual drilling operations are estimated from data available, and the mechanism of failure of drill steel in the as-rolled and surface-treated conditions is analyzed. The magnitude of the surface compression stresses and their effect on fatigue strength are discussed.

* * *

INTRODUCTION

SUCCESSFUL mining depends on numerous technical operations of which one of the most important is the drilling of holes in the ore and waste ground. These holes are filled with dynamite which, when exploded, shatters the rock, the beginning of all mining operations.

Mine drilling operations should be done economically, *i.e.*, at low cost and high speed. Many factors contribute toward perfection of drilling (1 to 26). In this paper we shall be concerned, in general, with the performance of the drill steel — *i.e.*, the drill set composed of bit, attachment, drill rod, and shank end — and, in particular, with the endurance strength and working conditions of one of them, namely the drill rod, and the possibilities of improving its endurance strength and actual field performance.

WORKING STRESSES IN DRILL STEEL

In typical mining operations such as cross-cutting, stoping, and sinking, the shank-end of the drill set is exposed to a hammering from the piston, directly or through an anvil in a collarless arrangement of a drilling machine. The magnitude of this hammering energy varies from about 20 to 180 foot-pounds per single blow, depending on the type and size of the drilling machine and on the air pressure used. A large portion of this energy is transformed into the cutting-crushing work of the drill bit. The remainder is lost in the vibration of the drill set, drilling machine, and rock; in the friciton of drill set in hole and drilling machine; and in numerous lesser ways.

Our drill set (see ref. 21 and Figure 1) is hammered on one end by the drilling machine. The number of blows depends on the type of machine used and varies from about 2,500 per minute for small machines to about 1,600 per minute for large drilling machines. From the bit end, the drill set is exposed to the reaction of the rock and ore being drilled. The dynamic stress distribution in a drill rod is of a complicated nature and the resultant pattern varies with time along the drill rod under consideration. In the simple case of a steel rod, freely supported at both sides and struck axially with a single blow, the tension-compression wave of stresses will travel back and forth from the struck end to the other end at the speed of sound in steel until this wave is damped out by the internal friction of the steel. When a similarly supported steel rod is struck with a large number of successive blows in evenly spaced time intervals, a resultant pattern of dynamic vibrational stress will be established. Analytical solutions of this pattern may be found in the literature. In the case of the drill steel the problem is more complicated, because the supporting conditions are difficult to define. During actual drilling operations, the bit end of the drill rod is supported in a semi-rigid manner in the rock and the other end is guided in the drilling machine. The definition of these types of supports is uncertain.

In order to determine the maximum values and the character of the stress pattern to which the drill set is exposed, and to simplify the whole problem, the direct measurement of stresses by SR-4 electrical strain gauges could be recommended as the best solution. Results of measurements of the distribution of dynamic stresses on a drill rod during actual drilling operations are given in Figure 1 as an illustration. These results were taken from a written discussion by F. R. Anderson, Chief Metallurgist, Gardner-Denver Company, of the paper presented previously (20). A number of conclusions could be drawn from this diagram, but at present only the large magnitude of dynamic tension stresses observed at the bit end (57,000 p.s.i. for sharp bit and 105,000 p.s.i. for dull bit) will be stressed.

The direct measuring technique, using SR-4 electrical strain gauges, is recommended for future programmes as the simplest way of obtaining data on the stress patterns of drill sets.

A general idea of the average value of the tension-compression cycle of dynamic stresses to which the bit part of the drill set is subjected could be approximately evaluated by calculating the average depth of a single chip and the impact resistance of the rock (2).

Depth of a single chip

= (Penetration ft. per min. × rotation (blows per turn)) divided by (Blows per min. × No. of points of bit)

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(19) For references see end of paper.

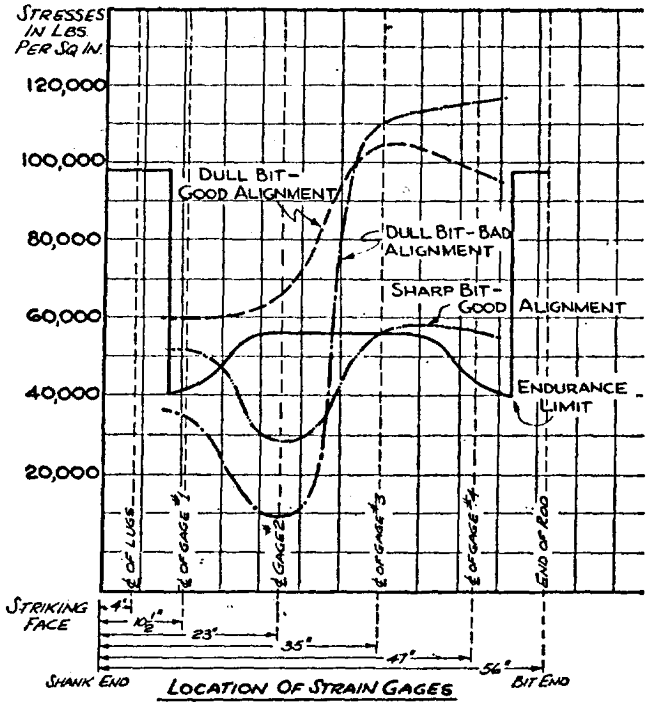
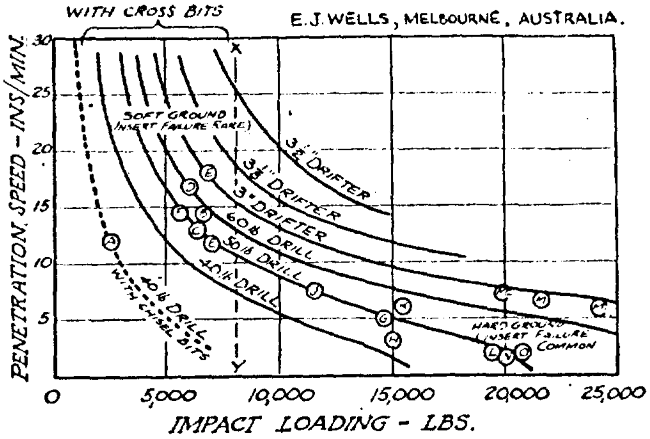


Figure 1.—Maximum tensile stresses in drill rod during drilling operation.

(From discussion by F. R. A. Anderson, see ref. 20)



PENETRATION SPEEDS OF TUNGSTEN CARBIDE TIPPED BITS FOR GROUND RANGING FROM HARD (BOTTOM, RIGHT OF CHART) TO SOFT (TOP LEFT) AND FOR SIX COMMON TYPES OF ROCKDRILL. AIR PRESSURE IS TAKEN AS 80 LB. PER SQ. IN. AND ALLOWANCES ARE MADE FOR 20 PERCENT LOSS OF ENERGY IN TRANSMISSION OF THE BLOW AND FOR THE APPROPRIATE VALUES OF THE COEFFICIENT OF RESTITUTION.

Figure 2.

(Impact resistance of rock × Depth of a single chip) equals energy of a single blow

The relations between impact loading (*i.e.*, impact resistance of rock) and penetration speed, given by E. J. Wells (2), are shown in Figure 2. This diagram is very interesting as it shows a number of important factors having a direct bearing on the life of drill steel, *i.e.*, the number of cycles to failure. These factors are listed below:

(1) Impact loading increases with the decrease of penetration speed, and *vice versa.*

(2) The harder the rock the lower the penetration speed and the greater the impact loading. Soft ground gives higher penetration speed and lower impact loading, thereby lowering stresses in drill steel; in hard ground the reverse is true.

(3) An increase in the size of the machine may increase the penetration speed and also the impact loading.

(4) With impact loading below 8,000 pounds, failures of the tungsten carbide (W-C) inserts are rare, but the probability of failure in the skirt, thread, and steel body of the bit before breakage of the tips is higher. Also, the probability of failure of the attachment, drill rod, and shank end is higher in this range, because of the longer life and greater number of blows (cycles of loading) which the bit tips can endure.

(5) With impact loading above 8,000 pounds, and hard rock conditions, the failure of the W-C inserts is more probable, especially with dull bits, as the rate of penetration for dull bits diminishes greatly and the impact load increases substantially.

Data on the stresses in the drill set, obtained from direct measurement by using SR-4 strain gauges, supplemented by the data on impact loading given by E. J. Wells and shown in Figure 2, give a good overall picture of the stress conditions existing in the drill set during field service. Figure 3 shows the *IR-N* relations set up from the test data presented by E. J. Wells (2).

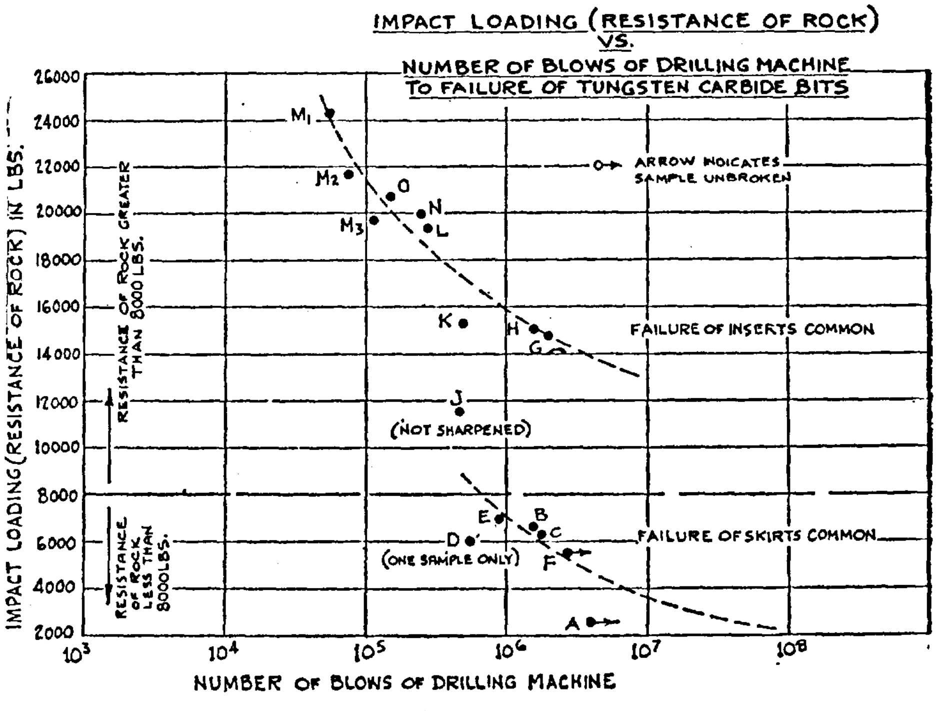


Figure 3.

REVIEW OF METHODS USED FOR TESTING DRILL RODS

The effect of different surface treatments on the endurance strength and field performance of drill rods could be evaluated in several ways.

One method would be the recording of: the total number of feet drilled until failure of the drill steel; the type of the failure, giving all data on the mining and operating conditions; and the information on the mechanical-metallurgical condition of the drill steel. This method would supply some relative data on field performance of different types of drill steel. These data could be reproduced only with the same operating and mining conditions, namely, using the same type of drilling machine, operated by the same operator, and duplicating such conditions as air pressure; hardness and structure of rock; penetration speed; sharpness, type, and size of bit; cross-section and length of the drill steel; and alignment and support of the drilling machine.

Another method would be the so-called 'block-test', during which both the time required to cause failure of the drill rod, and the type of failure, are recorded along with data on operating conditions such as type of drilling machine used, length of the drill rod, supporting conditions, air pressure, and so on. It should be noticed that in this method the drill rod sample is supported at one end in a pneumatic drill and the other end is hammered against a hardened steel plate. It was proved by B. M. Hamilton (15) that, because the amplitude of side vibration of the drill steel sample is influenced by its damping capacity, this method is erratic.

The conditions for reproducibility of these two methods are difficult to fulfil, but they are required if constancy of impact loading is to be maintained.

In order to simplify the study of the effect of different surface treatments on the fatigue limit and endurance strength of drill steel, the newly developed Canadian method of fatigue testing mining drill rods (19) has been used to determine the fatigue data discussed in this paper.

This method is simple, very low in cost, reproducible, and renders results in numerical values, *i.e.*, stress in pounds per square inch and number of cycles to failure. The *S-N* relations, determined for a fairly wide range of stresses, could be used for the preliminary evaluation of the different surface treatments.

TABLE I. - Fatigue Tests SAE 1080 Carbon Steel, Shot-peened and Drawn under Dry Conditions.

Sample No.	Bending moment (inch-pounds)	Maximum stress, psi (edge A and flat B)	No. of cycles to failure, x10^3
CT-3	7000	57,500	161
CT-4	6500	53,400	319
CT-2	6000	49,300	350
CT-10	6000	49,300	601
CT-5	5500	45,200	1,691
CT-12	5475	45,000	4,313
CT-9	5425	44,600	13,000*
CT-7	5375	44,200	12,000*
CT-6	5250	43,100	13,000*
CT-1	5000	41,100	6,500*
SR-1	Spiral-Rolled	61,500	1,055 (Ref. 23)

* Sample unbroken.

TABLE II. - Fatigue Tests of SAE 1080 Induction Hardened Carbon Steel under Dry Conditions.

Sample No.	Bending moment (inch-pounds)	Maximum stress, psi (edge A and flat B)	No. of cycles to failure, x10^3
AI-2	8500	69,900	42
AI-4	8000	65,800	76
AI-7	8000	65,800	74
AI-10	7500	61,600	77
AI-11	7500	61,600	113
AI-3	7000	57,500	718
AI-8	6500	53,400	1,420
AI-12	6375	52,400	4,854*
AI-5	6250	51,400	710
AI-9	6250	51,400	6,679*
AI-1	6000	49,300	8,030*
SR-1	Spiral-Rolled	61,500	1,055 (Ref. 23)

* Sample unbroken.

The final acceptance tests of a chosen type of surface treatment should be done during actual drilling operations and the results obtained in this way, supplemented by the simulated service test results, would determine whether the surface treatment under investigation could be recommended for adoption by industry.

FATIGUE TESTS

To study the effect of (*a*) shot-peening, (*b*) shot-peening and low draw, (*c*) induction surface hardening, (*d*) induction hardening and shot-peening, and (*e*) spiral-rolling on the endurance strength and fatigue limit, one-inch quarter-octagon drill rods made from Cr-Ni-Mo and plain carbon (SAE 1080) steel were used. The chemical compositions and the mechanical properties of these steels are given in reference 20 and Tables I and II.

The effect of different surface treatments on the fatigue properties of the Cr-Ni-Mo and SAE 1080 steels may be studied from the *S-N* diagrams shown in Figures 4 to 7 and from the numerical Tables I to VI.

Remarks

TABLE I:

All samples broke in the free gauge length with the exception of samples CT-4 and CT-12, which broke in the adaptors. Nucleus of fatigue failure was observed on edge *A* and octagonal flat *B* (19). Typical dual type fatigue fractures were observed, with two distinct zones, namely:

TABLE III. - Fatigue Tests of Ni-Cr-Mo Steel, Shot-peened and Tempered, under Dry Conditions.

	Sample No.	Bending moment (inch-pounds)	Maximum stress, psi (edge A and flat B)	No. of cycles to failure, x10^3
	GT-11	9500	78,100	499
	GT-8	9000	74,000	422
	GT-4	8500	69,900	1,016
	GT-1	8000	65,800	1,331
	GT-10	7875	64,700	2,881*
	GT-9	7750	63,700	4,725*
Spiral	SR-2	7000	57,500	6,000*
Rolled	SR-3	8000	65,800	6,000*
Ref. 23	SR-4	9000	74,000	6,000*

* Sample unbroken

TABLE IV. - Fatigue Tests on Ni-Cr-Mo Steel, Induction Hardened, under Dry Conditions.

	Sample No.	Bending moment (inch-pounds)	Maximum stress, psi (edge A and flat B)	No. of cycles to failure, x 10^3
	EI-12	9500	78,100	283
	EI-3	9000	74,000	356
	EI-7	9000	74,000	361
	EI-4	8500	69,900	1,637
	EI-8	8500	69,900	182
	EI-11	8500	69,900	568
	EI-2	8000	65,800	1,916
	EI-10	7937	65,200	4,643*
	EI-9	7875	64,700	5,683*
	EI-6	7750	63,700	6,722*
	EI-5	7500	61,600	5,635*
	EI-1	7000	57,500	5,450*
Spiral	SR-2	7000	57,500	6,000*
Rolled	SR-3	8000	65,800	6,000*
Ref. 23	SR-4	9000	74,000	6,000*

* Sample unbroken.

(1) A smooth matte surface (M1) (see ref. 19) resulting from a crack initiated at the nucleus of fatigue, progressing toward the internal water hoie, and battered smooth by repeated opening and closing of the crack taking place during each cycle.

(2) A rough crystalline surface (X2) (see ref. 19), indicating a sudden fracture resulting from overstressing.

The *Estimated Fatigue Limit* between samples CT-5 and CT-12 on the diagram is about 5,500 inch-pounds and 45,000 p.s.i.

TABLE II:

All samples broke in the free gauge length. The nucleus of fatigue failure was observed on edge *A* and octagonal flat *B*. In sample A1-5, nucleus of fatigue coincides with a local surface imperfection.

Typical dual type fatigue fractures were observed, with two distinct zones, namely:

(1) A smooth matte surface (M1) resulting from a crack initiated at the nucleus of fatigue, progressing toward the internal water hole, and battered smooth by repeated opening and closing of the crack taking place during each cycle.

(2) A rough crystalline surface (X2), indicating a sudden fracture resulting from overstressing.

The fracture surface is 30% M1 and 70% X2, except on samples A1-2 and A1-4 where it is 100% M1 with a progressive wave-like fracture.

An induction hardened 'skin' 1/64 inch thick was observed around the whole circumference.

The *Estimated Fatigue Limit* between samples A1-8 and A1-12 on the *S-N* diagram is about 6,400 inch-pounds and 53,000 p.s.i.

TABLE III:

All samples broke in the free gauge length, with the exception of GT-11, which broke at the edge of the attachment. The fracture is irregular, indicating toughness of this steel. The nucleus of fatigue failure was observed on edge *A* and octagonal flat *B*.

Dual type fatigue fractures were observed, with two distinct zones, namely:

(1) A smooth matte surface (M1) resulting from a crack initiated at the nucleus of fatigue, progressing toward the internal water hole, and battered smooth by repeated opening and closing of the crack taking place during each cycle.

(2) A rough matte crystalline surface (MZ1), indicating a sudden fracture resulting from overstressing.

The fractured surface is about 50% M1 and 50% MZ1.

The *Estimated Fatigue Limit* between samples GT-1 and GT-10 on the *S-N* diagram is about 79,000 inch-pounds and 65,250 p.s.i.

TABLE IV:

All samples broke in the free gauge length, with the exception of E1-3 and E1-4. The nucleus of fatigue failure was observed on edge *A* and octagonal flat *B*.

Typical dual type fatigue fractures were observed, with two distinct zones, namely:

(1) A regular matte surface (M1) resulting from a crack initiated at the nucleus of fatigue, progressing toward the internal water hole, and battered smooth by repeated opening and closing of the crack taking place during each cycle.

(2) A rough crystalline surface (MX1), indicating a sudden fracture resulting from overstressing.

The fracture surface is about 50% M1 and 50% MX1.

An induction hardened skin about 3/64 inch thick was observed around the whole circumference.

The *Estimated Fatigue Limit* between samples E1-2 and E1-10 on the *S-N* diagram is 8,000 inch-pounds and 65,500 p.s.i.

TABLE V:

All samples broke in the free gauge length. The nucleus of fatigue failure was observed on edge *A* and octagonal flat *B*, just below the induction hardened skin.

Typical dual type fatigue fractures were observed, with two distinct zones, namely:

(1) A regular matte surface (M1) resulting from a crack initiated at the nucleus of fatigue, progressing toward the internal water hole, and battered smooth by repeated opening and closing of the crack taking place during each cycle.

(2) A rough matte-crystalline surface (MX1), indicating a sudden fracture resulting from overstressing.

The fracture surface is about 50% M1 and 50% MX1.

The *Estimated Fatigue Limit* between samples E1S-9 and E1S-11 on the *S-N* diagram is 7,600 inch-pounds and 62,200 p.s.i.

TABLE V. - Fatigue Tests of Ni-Cr-Mo Steel, Induction Hardened and Shot-peened, under Dry Conditions.

	Sample No.	Bending moment (inch-pounds)	Maximum stress, psi (edge A and flat B)	No. of cycles to failure, $\times 10^3$
	EIS-1	10,000	82,200	303
	EIS-2	9000	74,000	651
	EIS-3	8500	69,900	2,350
	EIS-4	8375	68,900	1,524
	EIS-5	8375	67,900	956
	EIS-6	8250	67,800	1,482
	EIS-7	8125	66,800	2,213
	EIS-8	8000	65,800	2,504
	EIS-9	7750	63,700	2,284
	EIS-11	7375	60,600	9,323*
	EIS-10	7000	57,500	11,516*
Spiral Rolled (Ref. 23)	SR-2	7000	57,500	6,000*
	SR-3	8000	65,800	6,000*
	SR-4	9000	74,000	6,000*

* Sample unbroken.

TABLE VI. - Laboratory Drilling Time of Different Types of Drill Rods, Obtained on Type I Laboratory Drilling Machines under Dry Testing Conditions.

Load on Type I Laboratory Drilling Machine Bending Moment, inch-lb.	Maximum Stress, psi	Cycles to Failure (Drilling Time, Minutes) Untreated	Spiral-Rolled	Endurance Factor
One-inch quarter octagon Cr-Ni-Mo steel				
7000	57,500	350,000 (175 min.)	6,000,000< (3,000 min.)<	over 17
8000	65,800	282,000 (140 min.)	6,000,000< (3,000 min.)<	over 21
9000	74,000	80,000 (40 min.)	6,000,000< (3,000 min.)<	over 25
7/8 inch quarter octagon SAE 1080 steel				
5000	61,500	90,000 (45 min.)	1,055,000 (525 min.)	11.5
7/8 inch hexagonal, Ni-Cr-Mo "Nushank" steels A, B, C				
4000	57,000	216,000 (108 min.)	3,385,000 (1,690 min.)	15.5
4000	57,000	216,000 (108 min.)	4,200,000 (2,100 min.)	20
5000	71,250	75,000 (37 min.)	120,000 (60 min.)	1.6
5000	71,250	75,000 (37 min.)	135,000 (67 min.)	1.8
7/8 inch hexagonal Cr-Mo "Vibresist" type steel "V"				
5000	71,250	86,000 (43 min.)	5,127,000 (2,563,000)	over 60

DISCUSSION OF THE TEST RESULTS

The effect of induction surface hardening, shot-peening, and spiral-rolling on fatigue limit of SAE 1080 plain carbon steel in the as-rolled condition is shown in Figure 5 and in reference 20, Figure 3. *S-N* relations for SAE 1080 induction hardened, shot-peened and drawn, and spiral-rolled drill rods have been given in Figure 4. The intensity of shot-peening used was about 15 as measured on Almen strip *A*, and the temperature of draw was 450°F.

The fatigue limit of the SAE 1080 drill steel in the as-rolled condition is ±35,000 p.s.i. under rotating bending conditions. The fatigue limit of the same steel after shot peening increased to ±44,700 p.s.i., *i.e.*, 28 per cent; after shot-peening and draw, it increased ±45,000 p.s.i., *i.e.*, 28.5 per cent; and after induction surface hardening a fatigue limit of ±53,000 p.s.i., *i.e.*, a 51 per cent increase, was obtained. With the as-rolled condition as datum, the corresponding percentage increases of fatigue limits for different surface treatments are shown in Table VII.

In Figure 5 the *S-N* curves *A* and *B*, for dry and water corrosion conditions, cross above the fatigue limit of steel *A* at about a stress of 39,000 p.s.i., which shows that the water stress corrosion starts to be detrimental for a new drill steel after a million cycles (which are applied in about 14 hours). Up to that time the stress corrosion does not show a detrimental effect on the life of the drill steel; on the contrary, at high stress levels some beneficial effect of water cooling could be reported. The steeper slope of the curve *B*, *S-N* relations for the corrosion test, as compared with the slope of curve *A*, *S-N* relations for the dry test, shows that the required number of cycles to failure below the intersection point of these curves is considerably lower, and therefore the life of drill steel under water-corrosion conditions is much shorter than under dry conditions. For this steel a corrosion fatigue failure was obtained under a stress as low as 16,500 p.s.i.

Shot-peened surfaces, besides increasing the endurance strength and fatigue limit of steel SAE 1080 as shown in Figures 4 and 5, reduce considerably the effect of the increase of slope of the *S-N* curve due to water corrosion; the same could be expected after induction hardening. The life of *D* steel is greatly increased as compared to *B* steel.

The effects of the various surface treatments, *i.e.*, induction surface hardening, shot-peening, spiral-rolling, and induction surface hardening and shot-peening combined, on Ni-Cr-Mo steel are shown in Figures 6 and 7 and Tables III to VII. A few of the many practical conclusions which could be drawn from the results obtained are discussed below.

In Table VII, where the effects of different surface treatments on the fatigue limits of Ni-Cr-Mo steel are shown and where their percentage increases compared to SAE 1080 and Ni-Cr-Mo both in the as-rolled condition are given, the beneficial effects of all types of surface treatments discussed are obvious.

In Figure 7, the *S-N* relations obtained from steels *E* and *F* enable the following observations to be made.

As mentioned previously, in the case of drill steel SAE 1080 the effect of water corrosion on the *S-N* relations in the damaging range of stresses, *i.e.*, above the fatigue limit, also has a tendency to increase the life of the Ni-Cr-Mo drill steel in our testing conditions. The curves *E* and *F* cross each other in a characteristic point at about a stress of 53,500 p.s.i., which is above the fatigue limit for the as-rolled condition. Below this characteristic intersection, curve *F* is fairly close to a straight continuation of the curve *E* for dry conditions above the fatigue limit.

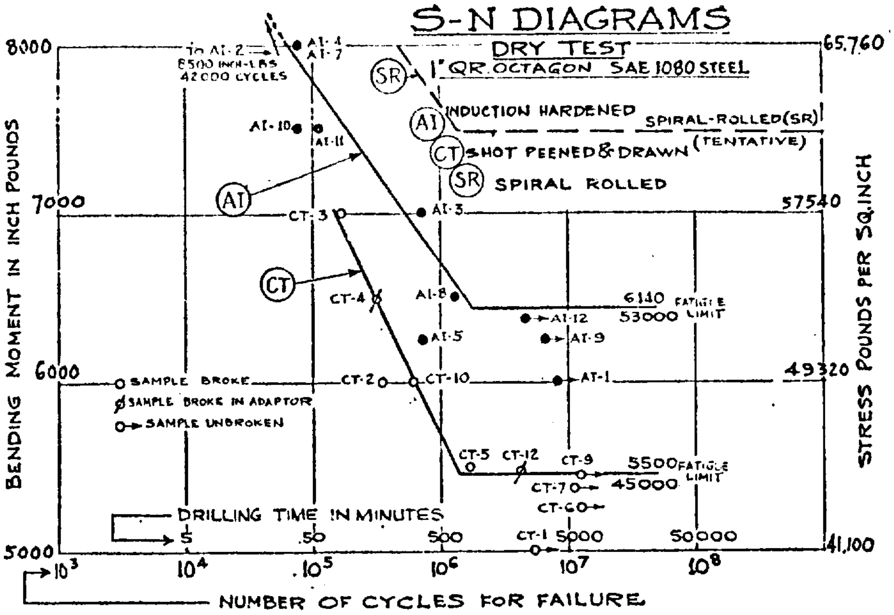


Figure 4.

The beneficial effect of the shot peening of Ni-Cr-Mo drill steel, as shown by the relative position of the *E* and *G* curves (Figure 7), is characterized by a large increase of fatigue limit (about 17,000 p.s.i., 36%) and by a large increase of the life of drill steel for stresses above the fatigue limit of *G* steel. This increase diminishes in the higher stress range because of a lower slope of curve *G* as compared with *E*, The *S-N* curves *F* and *H* are almost parallel on a semi-logarithmic scale for shot-peened and un-peened specimens of steel under water corrosion conditions, and for the same life (*N*) the stress is increased by about 30,000 p.s.i. The increase of the slope of the *H* curve in relation to the *G* curve illustrates the possibility of a beneficial effect of water cooling in the higher range of stresses, *i.e.*, above the fatigue limit of *G* steel.

The beneficial effect of shot peening is comparable to that of induction surface hardening in the case of Ni-Cr-Mo steels, but spiral-rolling (23, 24) is much more effective than either shot peening or induction surface hardening.

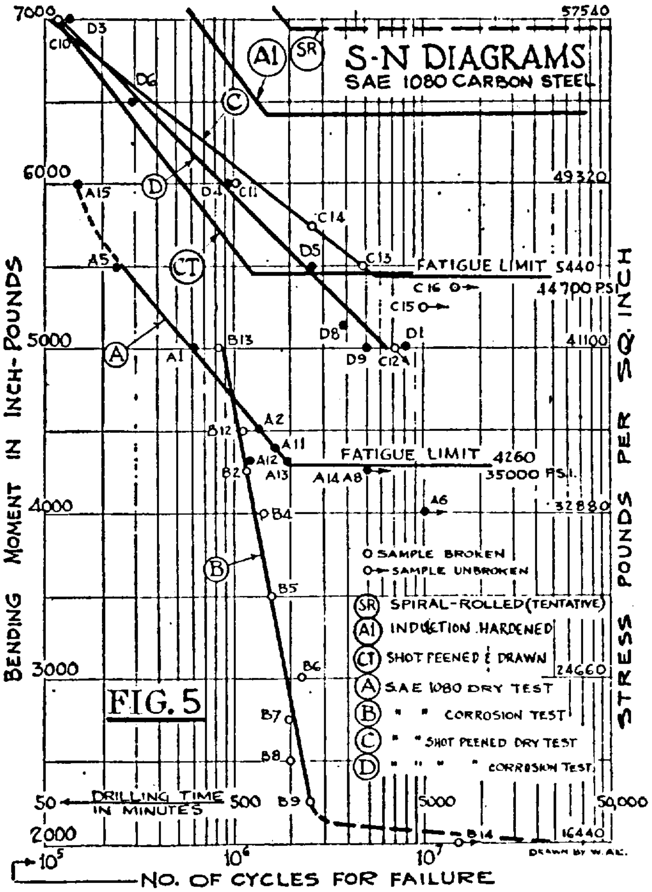


Figure 5.

THE MECHANISM OF THE STRENGTHENING EFFECT OF SURFACE TREATMENTS

All service failures of drill rods are attributable to some type of fatigue failure, and in order to predict the field performance of available drill steels the most logical way would be to determine the *S-N* relations for dry and water corrosion conditions under laboratory simulated service conditions, a method introduced previously (19, 20).

In order to explain the mechanism of the strengthening effect of the different surface treatments discussed, it is first necessary to know, in general, the mechanism of the failure of metals in fatigue, particularly the drill steel under consideration.

The mechanism of failure of drill steel under alternating stresses will be explained in a simplified manner in the following paragraphs:

When the magnitude of an externally applied dynamic load reaches a value which will produce, along various atomic crystal planes, a shear stress which exceeds the elastic limit in shear, a local plastic deformation (a slip of atomic planes) takes place. During this local initial plastic deformation, the so-called strain hardening or cold work phenomenon appears, and if the magnitude of the resultant alternating shear stresses resolved along the atomic planes showing the least resistance to slip of atoms is not large, further slip is stopped and the metal does not show further local changes. This is the safe range of stresses, and failure is not expected.

If the external alternating load exceeds a critical value, local plastic deformation will be produced which will exceed the limiting range of crackless deformation, and small cracks or discontinuities will result. During further alternating loading these local cracks start to grow in number and size, and if they reach a critical saturation a nucleus of fatigue is formed and the metal fails.

On the as-rolled surface of mining drill rods, a large number of local pits, sharp notches, and a variety of irregularities of geometrical and metallurgical origin, may be seen. These surface imperfections have their origin in the solidification of ingots in molds with irregular surfaces, and are formed during rolling operations by the impressions of the oxidation products from the heating of the ingot in the furnace.

These surface imperfections, because of their characteristic geometrical irregularities, introduce large local stress concentrations. The stress concentration factors of these irregularities may range up to 2 or 3, *i.e.*, the actual stress may be two or three times the normal stress obtained by direct measurements or by calculations. Its value depends on the radius of the root of the notch, *i.e.*, its sharpness, and on the dimensions of the section. The presence of these surface notches produces local overstressing, which in turn causes local plastic deformation at their roots. As long

TABLE VII. - **Comparison of Effect of Different Surface Treatments on Fatigue Limit, under Dry Conditions.**

	FATIGUE LIMIT	
	In Per Cent (As rolled = 100)	In psi
A. SAE 1080 Steel		
As rolled	100	±35,000
Shot-peened	128	±44,700
Shot-peened and drawn	128.5	±45,000
Induction surface hardened	151	±53,000
S.R. - Spiral-Rolled	175 appr.	±61,500
B. Ni-Cr-Mo Steel		
As rolled	100	±47,800
Shot-peened	135.5	±64,750
Shot-peened and drawn	137	±65,250
Induction surface hardened	137	±65,500
Induction surface hardened and shot-peened	130	±62,200
S.R. -Spiral-Rolled	over 155	over ±74,000

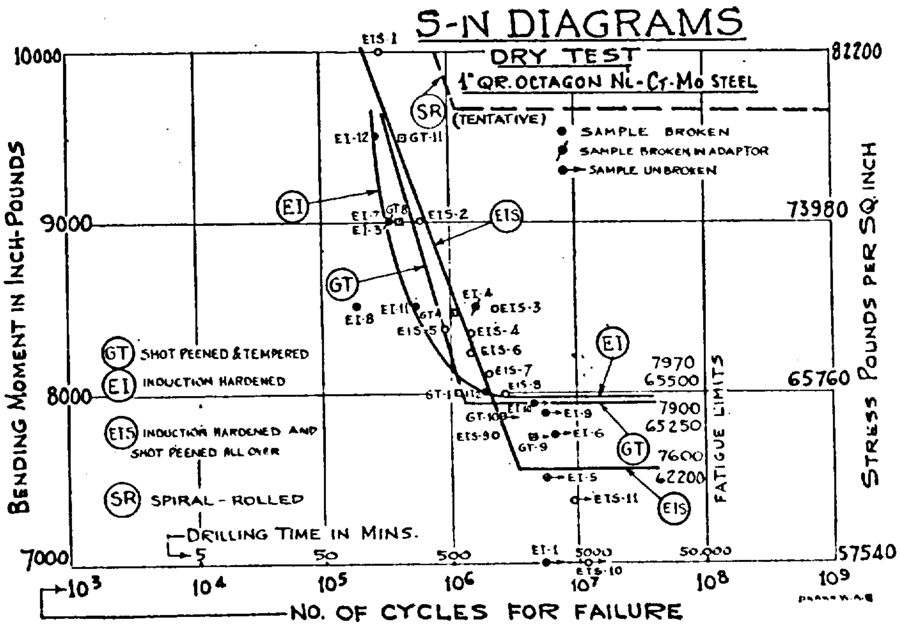


Figure 6.

as this plastic flow does not exceed the critical amount, that is, as long as it remains in the crackless region, the large local stresses are relieved during cyclic loading, but if the critical amount of mixed-up plastic flow under tension-compression stresses is exceeded, the nucleus of fatigue failure will be formed.

In the majority of mechanical elements the maximum stress appears at the outside surface and it is therefore clear that the nucleus of fatigue failure will be formed on the outside surface.

Fatigue fracture of mining drill rods is, as a rule, of a duplex character: the fracture starts from the nucleus of fatigue, usually coinciding with the point of expected maximum stress, and from a local stress concentration, *e.g.*, a surface imperfection. The presence of this nucleus introduces a very sharp notch, and the failure continues progressively during cyclic loading until the uncracked portion breaks suddenly due to overloading. In a progressive fatigue failure, the area of fracture adjacent to the nucleus is smooth because the surface is rubbed by the oscillating tension-compression load. This part of the fatigue fracture sometimes shows radially progressing circular rings with the centre in the nucleus. The area broken last is undamaged and is coarser and more crystalline in appearance than the first part.

To the above simplified picture of fatigue failure the effect of water corrosion on the outside surface is added. Under water corrosion, the formation of a large number of nuclei of fatigue failures will be greatly accelerated and, the corrosive action of water being intensified by the action of local stress concentrations, a large number of local intensive stress raisers in the form of sharp pits will be produced.

The presence of surface decarburization introduces a layer of metal of lower mechanical strength as compared with the core of the drill rod. Therefore, a lower fatigue strength should be expected for a drill rod with surface decarburization, as compared with a rod with a non-decarburized surface.

The shot-peened surface of a drill rod has a much higher fatigue limit and endurance strength under dry and water corrosion conditions than has the unpeened surface, as may be seen from the *S-N* diagrams shown in Figures 4 to 7.

Using the previously described mechanism of failure in fatigue, the beneficial effect of shot peening could be explained as being a resultant of the following phenomena:

(1) The smoothing of the rough and irregular surface of as-rolled drill rod by the impact and cleaning action of cast iron shot striking the rod in large quantities and under high velocity. The direct effect is the reduction of the stress concentration at the roots of numerous notches at the surface.

(2) The cold-worked thin surface layer has higher mechanical properties such as yield and ultimate tensile strength and, therefore, has higher fatigue strength.

(3) Locked-in, high, surface-compression stresses introduced by large plastic deformation through intensive shot peening. These stresses are mainly responsible for improving the fatigue strength of drill rods.

These surface-compression stresses are built up by the elastic recovery of the plastically deformed thin outside layer. At present all types of drill rods are decarburized on the surface to a depth depending on the chemical composition of the steel, the temperature and oxidation intensity of the furnace atmosphere, and the time exposed during the heating and rolling operations. Hence, the shot peening treatment will affect primarily the rough as-rolled and decarburized surface.

The locked-in compression stress, when superimposed by working stress, gives a resultant surface stress during tension loading which is lower than the tension working stress by the magnitude of the residual stress locked-in during shot peening. In compression loading, the compression working stresses are increased by the same amount.

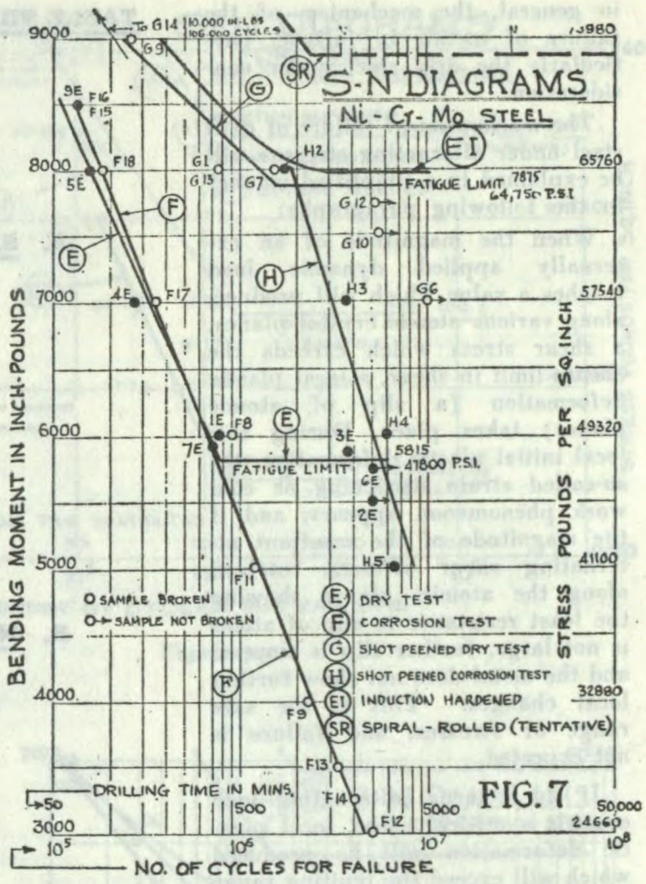


Figure 7.

The upper limit of the locked-in compression stresses introduced by shot peening is limited by the yield strength of the outside decarburized surface. The maximum possible increase in fatigue limit which may be obtained by shot-peening would be determined by a comparison of the fatigue limit of an as-rolled drill rod with the fatigue limit of a smoothly machined drill rod after shot-peening.

In general, the mechanism of the beneficial effect fo the shot-peening of drill steel could be explained by the three factors listed above. The influence of the third factor, *i.e.*, locked-in compression stresses, should be regarded as the most effective.

The mechanism of the improvement of fatigue strength of drill steel by induction surface hardening is somewhat different from that of shot-peening. In this type of surface treatment the following phenomena contribute to the improvement of the fatigue strength of the drill steel:

(1) In the decarburized zone the induction hardened surface has a much higher hardness and, therefore, a higher fatigue limit. However, the quenching of induction

heated, rough, as-rolled surfaces might increase the number of surface cracks and also might increase previous irregularities and sharpness of the roots of notches in the outside surface of drill steel; all of which could have a detrimental effect on fatigue strength.

(2) The induction hardened surface layer or case, of a depth of about 20 to 50 thousandths of an inch, is exposed to residual thermal stresses built up during the quenching of the induction hardened surface. These stresses are introduced by the changes of volume taking place during the transformation of austenite into martensite. If these volume changes are greater than the average thermal contraction coefficient, this could account for substantial locked-in compression stresses.

These two phenomena would be mainly responsible for the increase of the fatigue strength, noticed in our research.

Taking into consideration the beneficial effect of shot-peening, it would be reasonable to expect that the induction surface hardening treatment followed by shot-peening could further improve the laboratory fatigue performance of drill steel. The *S-N* relations for this combined treatment are shown in Figure 6, curve *EIS*. A small drop of fatigue limit in the *EIS* curve, as compared with the *EI* and *GT* curves, shows that the expected beneficial effect of surface treatment had reached its optimum and that any additional effort to increase the effect of locked-in surface stresses is not effective, even might be detrimental.

The mechanism of the improvement of fatigue strength of drill steel through spiral-rolling treatment is based on the principle of the so-called differential plastic deformation — through the impression of one or more spiral (helical) grooves into the surface of the drill steel, as shown in Figure 9.

The interlocking of areas with different amounts of plastic deformation, *i.e.,* large deformations in the valleys and smaller or no deformations at the peaks of the impressed grooves, is responsible very substantially for the durability of the spiral-rolled (S.R.) drill steel. Further data on the application of spiral-rolled drill steel are given in the references 23 and 24.

In Figure 8 are shown the results of the hardness test of a longitudinal section of induction surface hardened SAE 1080 and Ni-Cr-Mo drill rod. The plain carbon steel (1080) shows two distinct hardness zones: (1) a surface zone decarburized to a depth of about 0.004 inch, with a hardness range of 39 to 59 Rockwell *C* and the possibility that the outer 0.001 inch of its thickness may have a lower hardness; (2) an inner, fully hardened zone about 0.016 inch thick and having a hardness range of 64 to 67 Rockwell *C*. The transition zone between the second zone and the core has a very sharp drop of hardness, as may be noticed in Figure 8.

The induction hardened case of Ni-Cr-Mo steel is composed of three distinct zones. The first zone, about 0.004 inch thick with a hardness about 56 Rockwell *C*, coincides with the outside decarburized layer of drill steel. The second zone, about 0.022 inch thick with a hardness range from 62.5 to 65 Rockwell *C*, is the fully hardened case. The third transition zone is 0.018 inch thick, with a hardness range 52 to 46 Rockwell *C*. The microstructure of these zones is martensite with some retained austenite and a wide range of austenite-martensite transformation products.

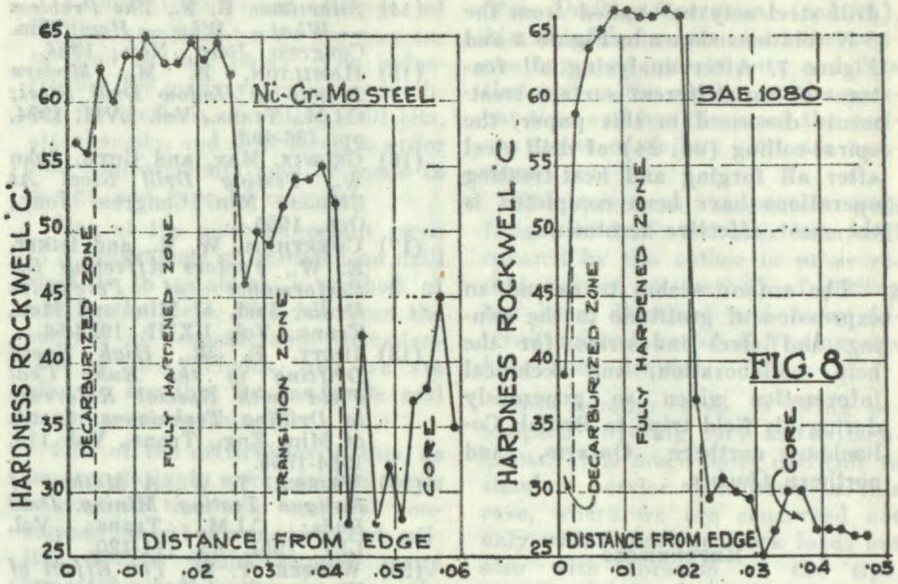


FIG. 8

HARDNESS DIAGRAM OF INDUCTION HARDENED DRILL STEEL

Figure 8.

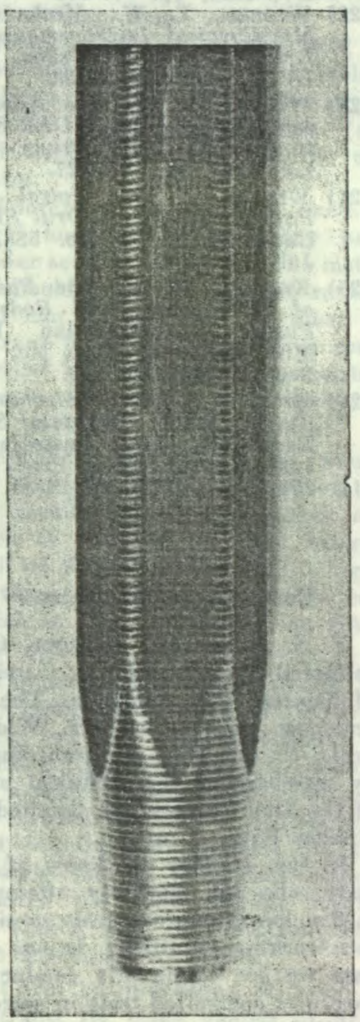


Figure 9. — Spiral-rolled drill steel with tapered attachment.

CONCLUSIONS

The results of this research indicate that shot-peening, induction surface hardening and spiral-rolling produce substantial increases in the fatigue limit of drill steel. These increases in the fatigue strength of drill steel may be studied from the *S-N* relations shown in Figure 5 and Figure 7. After analyzing all features of the different surface treatments discussed in this paper, the spiral-rolling (23, 24) of drill steel after all forging and heat-treating operations have been completed is the most effective treatment.

The author wishes to extend an expression of gratitude to the mining and steel industries for the help, collaboration, and technical information given so generously during his field trips to British Columbia, northern Ontario, and northern Quebec.

REFERENCES

(1) BLOEMSMA, J. H., RAMSAY, R., and DEANE, O., *Some Experiments with Tungsten Carbide Tipped Drill Steel;* Chem. Met. and Min. Soc. of South Africa, Jour., January, 1947.

(2) WELLS, E. J., *Percussion Rock Drilling with Tungsten Carbide Tipped Bits;* Chem. Eng. and Min. Review (Australia), January, 1949.

(3) LEWIS, James E., *Notes on the Engineering Design of Tungsten-Carbide Rock Bits;* Australasian Inst. Min. and Met., March, 1950.

(4) BOGAN, L. C., *Notes on the Metallurgical Design of Tungsten Carbide Rock Bits;* Australasian Inst. Min. and Met., March 1950.

(5) BELL, Donald H., and CLARKE, Paul E., *Tungsten-Carbide Drilling Investigations at Morning Star (G.M.A.) Mines, N.L.;* Australasian Inst. Min. and Met., Paper No. 19, March, 1950.

(6) ANTILL, J. M., and REA, J. L., *Experiences in Rock Drilling with Tungsten Carbide Tipped Bits;* Instit. of Eng., Australia, Jour., Vol. 23, No. 6, June, 1951.

(7) MCCORMICK, W. H., and PERSONS, R. W., *Trends in Hollow Drill Steel;* Min. Congress Jour., Sept., 1952.

(8) WILLIAMS, E., and WEARNE, C. E. Caldwell, *Mining Methods at Mount Morgan Limited;* Australian Inst. Min. and Met., Paper No. 26, August, 1952.

(9) ANDERSON, Floyd R., *Mechanical Treatment of Drill Steel;* Min. Congress Jour., Nov., 1954.

(10) MARCOTTE, R. J., *Control — The Payoff;* Min. Congress Jour., Nov., 1954.

(11) NORMAN, T. E., *Materials, Treatment, and Design for Drill Rods;* Min. Congress Jour., Nov., 1954.

(12) PAYSON, Peter, *Heat Treatment;* Min. Congress Jour., Nov., 1954.

(13) TOWNE, William F., *Development of Materials for Hollow Drill Steel;* Min. Congress Jour., November, 1954.

(14) SHEPHERD, B. F., *The Problem — What — Why — How;* Min. Congress Jour., Nov., 1954.

(15) HAMILTON, B. M., *Modern Trends in Hollow Drill Steel;* C.I.M., Trans., Vol. LVII, 1954, pp. 486-493.

(16) GELWIX, Max, and GOTH, John W., *Testing Drill Steel At Climax;* Min. Congress Jour., Oct., 1955.

(17) CHEETHAM, W. R., and INETT, E. W., *Factors Affecting the Performance of Percussive Drills;* Inst. of Min. and Met., Trans., Vol. LXIII, 1953-54.

(18) INETT, E. W., *High Speed Drifting in the Ruhr Coal Field with Special Reference to Drilling Techniques;* Instit. of Min. Eng., Trans., Vol. 114, 1954-1955.

(19) WLODEK, T. W., *A Method of Fatigue Testing Mining Drill Rods;* C.I.M., Trans., Vol. LIV, 1951, pp. 111-120.

(20) WLODEK, T. W., *The Effect of Water Corrosion and Shot Peening on Fatigue Strength of Mining Drill Rods;* C.I.M., Trans., Vol. LV, 1952, pp. 292-300.

(21) WLODEK, T. W., *Mechanical-Metallurgical Problems Associated with Mine Drilling Operations;* C.I.M., Trans., Vol. LV, 1952, pp. 377-383.

(22) WLODEK, T. W., *Mechanical-Metallurgical Improvements in Drill Steel;* C.I.M., Trans., Vol. LVIII, 1955, pp. 52-58.

(23) WLODEK, T. W., *The Application of Spiral-Rolled Drill Steel in Canada;* C.I.M., Trans., Vol. LX, 1957, pp. 124-127.

(24) WLODEK, T. W., *Spiral and Pattern Rolling of Drill Steel;* Canadian Patent No. 528,010, July 17, 1956.

(25) KEMSLEY, D. S., *The Failure of Steel Rock Drill Rods by Fatigue;* Australasian Inst. Min. and Met., Proc., No. 175, Sept., 1955, pp. 1-19.

(26) KEMSLEY, D. S., *Mechanical Factors in the Fatigue of Steel Rock Drill Rods;* Australasian Inst. Min. and Met., Proc., No. 175, Sept., 1955, pp. 21-34.

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CONTRIBUTED DISCUSSION

F. S. ANDERSON, Director, Consolidated Zinc Proprietary, Limited, Melbourne, C.I. Australia: The interesting papers by Mr. Wlodek (refs. 19, 20, 21) have been studied by members of the technical staff of the Zinc Corporation, Limited, at Broken Hill.

In this country we know of nobody who has similarly attempted to develop laboratory tests to simulate working conditions. In our own case we are continually conducting carefully controlled tests in selected locations in the mine. Apart from a series of block impact tests (which, when related to actual drilling tests, proved that the former were worthless as a short cut to determining the relative fatigue life of various drill steels), all work has been done by tests under operating conditions.

One reason we have not seriously considered research on the general lines Mr. Wlodek is using is that we have an extraordinarily wide range of drilling conditions and find that performance is sometimes more a function of the conditions than of the equipment.

We wish to make the following comments:

(1) That before continuing much further on the lines discussed in the papers mentioned, it might be wise to conduct, with the same steels, a series of field tests in each of several rock types, to ascertain what correlation there is between the test results and those obtained in field work.

(2) That our experience is that most fatigue failures start from the water hole and not from the outside fibres, so that we have considerable doubt as to whether the test method described does stress a rod in a manner approaching conditions met in practice.

(3) That in view of (2), the effects of surface treatments deduced from the tests might well not be closely borne out by field tests.

AUTHOR'S REPLY: Mr. Anderson's comments on block impact tests are convincing and we agree that this method should not be recommended for the determination of the relative fatigue life of various drill steels because of reasons given in our papers.

Using the simple Canadian method (refs. 19, 20, 21) for the relative laboratory evaluation of the performance of drill steel and attachments, we may correlate obtained *S-N* data with the actual field performance by assigning a corresponding impact resistance of rock to the proper stress level. The selection of a proper stress for different mining and operating conditions is recommended in our ref. 22 and is based on E. J. Wells' paper published in Australia (ref. 2).

We are attempting to correlate the data obtained from the Canadian methods of testing with the field performance using the technique given in our paper (refs. 21, 22). In our simulated service test, only the outside fibres were exposed to the maximum reverse-bending loading and therefore the results obtained reflect only the fatigue characteristic of the outside surface of drill steel and attachment. Usually the existing outside surface imperfections combined with the bending stresses favour the location of the nucleus of fatigue failure there. If the fatigue failures start from the water-hole it would indicate that the inside surface is less perfect and, additionally, that the internal stress-corrosion is more intensive.

George M. Dick, Chief Engineer, Canadian Ingersoll-Rand Company, Limited: One of the most important factors in many mining operations is cost. And one of the costly operations in most mines is drilling. Any method of decreasing the cost of drilling must be heartily welcomed by those in the mining industry, as well as by those associated with it. Mr. Wlodek has done some very fine work through his fatigue testing methods in helping to develop means of increasing the life of drill steel, and for this he is to be congratulated.

First Mr. Wlodek developed the testing methods which he described in his paper entitled *A Method of Fatigue Testing Mining Drill Rods* (19). Now he is using these fatigue testing methods in useful study of various treatments to drill steel. The results in his study of the shot peening, the induction hardening, and the spiral rolling treatments are most interesting.

It has been known for some time that surface treatments which will cause the surface layer to be in compression will increase the fatigue life of metals. Comparisons between the effectiveness of different treatments, however, have not been so forthcoming, and it is the job of a good testing method to correct this and promote further study to the improvement of drill steel.

The most effective surface treatment for one kind of steel is not necessarily the best treatment for another steel. In the Ni-Cr-Mo steel, shot peening is slightly more effective than induction hardening, but there is little choice between them. In the SAE 1080, however, induction hardening has considerably more effect than shot peening. It is very interesting to note that, as a result of Mr. Wlodek's latest investigations, spiral rolling of drill steel after forging and heat treating operations has been shown to be most effective surface treatment. The best treatment, or combination of treatments, must be determined for every steel, and the effect can now be measured.

As manufacturers of all types of drilling equipment we were very interested in this paper. The industry has for many years been searching for methods of testing drill bits, attachments, and drill steel, in order that improvements may be made in design and type of material.

One of the most important steps in a programme of research on drill steel is to establish a method of testing the steel. This has been the subject of considerable investigation by Mr. Wlodek, and we are glad to see that he has made real progress along this line.

One of the difficulties in this, as in any fatigue work, is the large amount of time and material consumed. To test one piece to five million cycles would require many hours of actual testing, to say nothing of the time consumed in preparation of the specimen.

The other difficulty which comes to mind is that of determining and duplicating actual field conditions in order that a comparison may be made between test results and actual drilling time.

Actual stressing in the field is governed by a number of variables, including straightness of steel, type of rock, operating conditions (air and water pressure), and the operator.

Therefore, no testing method could hope to duplicate any particular service conditions. The method should, however, produce results that can be compared to those in average mine conditions. This comparison should be the measuring stick in determining the virtues of any particular testing method.

Speaking generally, we would say that our experience corroborates the results which Mr. Wlodek arrives at, namely, that the fatigue limit of Ni-Cr-Mo drill steel is higher than that of Cr-Mo drill steel, which in turn is higher than SAE 1080 steel.

The method described should be very useful to manufacturers of drill steel, and also to heat-treaters, in determining the optimum conditions for maximum life of drill steel under normal conditions. Apparently, shot peening will increase the endurance limit of drill steel several hundred per cent. Similar results are shown with the induction surface hardening treatment.

It will be interesting to see *S-N* diagrams for other shapes of drill steel (hexagon, round, etc.) as well as for other types of steel.

In his paper *Mechanical-Metallurgical Problems Associated with Mine Drilling Operations* (ref. 21), Mr. Wlodek has described the various types of attachments and bits that are on the market at the present time and has discussed the various types of failure that are common.

The problems associated with fatigue in drill steel have been well covered by the author in other recent papers. A method of testing has been described and many interesting and useful *S-N* diagrams have been drawn.

Now similar work is being attempted covering bits and attachments. It is much more difficult to simulate service conditions in this case, where we are concerned not only with impact or shock loads but also with abrasion of the tips, abrasion on the gauge, shear in the braze material, water corrosion, etc.

Probably more than one test will be necessary to evaluate tungsten carbide tipped bits. Mr. Wlodek has described one method of testing bits and attachments in fatigue. In this test the impact stress encountered in practice is duplicated to a certain extent. The value of this method, however, will not be proven until further tests have been performed. The ideas behind this testing method are sound and we see no reason why this should not be a good method of testing bits and attachments. Water corrosion conditions may also be followed in this method.

The other method of fatigue testing with which we are familiar is that of actual drilling in granite or other rock and measuring the number of feet drilled before failure of the bit. This is a costly procedure, although probably faster than the laboratory method described. Other disadvantages of this method are that it is so noisy and dirty that it could not possibly be performed in the laboratory. Quiet laboratory tests such as those described by Mr. Wlodek are much to be preferred if they are proven satisfactory.

Author's Reply: In reference to Mr. Dick's comments, the effect of variables influencing the field stressing conditions could be taken into consideration by selecting a test load to obtain a number of cycles to failure-equivalent to time of actual drilling. We do not expect difficulties in determining the relative performance of different drill steels using our testing methods.

As proposed by Mr. Dick, the widening of our research work to include various shapes and types of drill steel is gradually taking place. Table II in ref. No. 22 gives analytical data indicating what could be expected from different shapes of drill steel.

We are very hopeful as to the effectiveness and usefulness of our proposed methods of fatigue testing of drill steel and conical and threaded drill rod attachments — our Types I, II, and III laboratory drilling machines; but we share Mr. Dick's opinion about existing difficulties in simulating working conditions of bits. Therefore, our programme at present does not include the development of machines for bit tests.

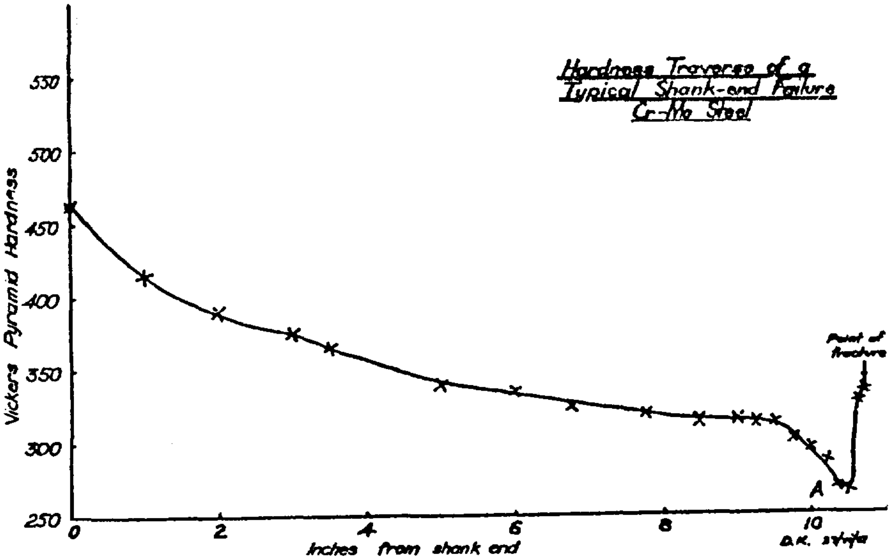
The above discussions represent only a portion of the comments and inquiries received in connection with metallurgical and mechanical problems related to mine drilling.

These comments and inquiries, for which the author is very grateful, have proven to be extremely helpful in stimulating further work on the solution of these problems.

D. S. Kemsley, School of Mines of W. A. Kalgoorlie, Western Australia: I have read your paper entitled *A Method of Fatigue Testing Mining Drill Rods* (ref. 19), in which I was deeply interested.

As you are probably well aware, the shank-end fatigue failures in drilling practice begin either at the water hole or at the outside surface, the distribution being roughly 50 per cent of each type.

It seems that the majority of shank-end failures are occurring within about 1/8 in. of each side of the valley at *A*, corresponding to the end of the heat-treated zone, and shown on the accompanying hardness diagram of a typical shank-end failure.



Hardness traverse of a typical shank end failure.

I understand that such failures are occurring in the copper belt of Northern Rhodesia, and at Wittenoom Gorge in W.A., as well as at Kalgoorlie. I would welcome your comments on the incidence of this phenomenon in the Canadian mining industry, where forged shanks are employed.

Have you done any work on fatigue testing of drill rods with heat-treated shanks, using the newly developed Canadian method of a laboratory simulated service test of drill steel?

Author's Reply: In answer to Mr. Kemsley's discussion I will refer to our papers already published and to technical data collected for papers which we intend to publish in the near future.

Metallurgical Notch in Drill Steel

Mr. Kemsley's observations that the shank fatigue failures begin either at the water-hole or from the outside surface, in both cases mostly at the section of the lowest hardness, the valley *A* of the hardness pattern, agree, with our observations made in Canada.

The so-called 'metallurgical notch', the softest section of the drill steel at the heat-transition zone between the heated and as-rolled part of a mining drill rod, is the weakest portion and usually fails in fatigue.

A typical hardness pattern of a heat-treated conical attachment made from 7/8-inch quarter octagon Ni-Cr-Mo steel is shown in Figure 8, ref. 22.

The simulated service test employing our Canadian method of fatigue testing drill steel (ref. 19) supports Mr. Kemsley's observations made in Australia.

The results of fatigue testing in the area of the metallurgical notch are as follows: at the stress level ±73,800 p.s.i., the expected time of drilling is reduced from 52 minutes, on the as-rolled portion of the drill rod, to 23 minutes, *i.e.*, 56 per cent, on the portion of rod having the metallurgical notch. At the stress level ±61,500 p.s.i. the time of drilling is reduced from 118 minutes for the as-rolled condition to 61 minutes at the metallurgical notch. This detrimental effect of metallurgical notch is unavoidable for the heat-treated attachment and could be remedied by shot-peening, as is shown in the first series of reports published on mine-drilling (refs. 19, 20, 21) or by spiral-rolling (refs. 22, 23).

Fatigue Strength of Heat-Treated Drill Steel

We share fully Mr. Kemsley's interest in the study of the effect of heat-treatment on drill steel. The Canadian method of drill-rod testing should be extended to all practical applications in mine drilling research, but our lack of time is delaying the publication of this interesting data.

The *S-N* relations obtained on S.A.E. 1080 carbon steel in the as-rolled, shot-peened, oil-quenched, and oil-quenched and shot-peened conditions, are very interesting.

If for comparison purposes we choose a load level ±53,500 p.s.i. and assume 100 per cent drilling time (80,000 cycles) for as-rolled conditions; 250 per cent (225,000 cycles) for the as-rolled and shot-peened; and 1,400 per cent (1,250,-000 cycles) for rods quenched in oil and for quenched and shot peened, even higher performance could be expected.

The above two topics mentioned in Mr. Kemsley's discussion are very interesting and characteristic of the large variety of mechanical-metallurgical problems existing in mine drilling operations.

Olaf Troili, Metallurgical Engineer, Johannesburg, South Africa: We have learned with great interest about the fatigue testing machine, for mining drill rods, developed by you (ref. 19).

We have, in South Africa, a special problem because of drilling techniques which quite often involve 'dry drilling', *i.e.*, drilling without water for sludging. This is particularly the case with a great number of quarries and small mines.

When drilling dry, the bit-end of the steel is heated to a considerable extent (about 100 to 200°C.). Tungsten carbide tipped Cr-Mo alloyed steels of the Diesel-bit type are employed (approx. analysis of the steel 1.0% C; 1.0% Cr; 0.30% Mo).

There is a tendency for the steel to break off a few inches from the bit end where low hardness (22 to 28 Rc) was obtained at brazing. This type of steel failure occurs more frequently in 'dry drilling' than in wet drilling.

It would be of interest if the *S-N* curves for a Cr-Mo alloyed steel of the above type could be determined at increased temperature. The steel should be treated in a similar way as in the brazing operation (heating to about 1,000°C.) so as to get a soft zone.

It would interest us to know whether you have planned to include a test as above in your research programme.

Author's Reply: With the data already on hand we hope to be able to provide Mr. Troili with the answers and some illustrative information without performing actual laboratory tests.

The temperature during dry-drilling is estimated by Mr. Troili to be between 100° and 200°C. Since, in our laboratory drilling machine Type I, we have also observed a comparable heating of the drill-rod sample, especially in the high range of stresses, we can assume that our *S-N* relations obtained under dry conditions are similar to dry drilling. Also our *S-N* relations obtained under water corrosion conditions are comparable to his drilling with water used for sludging.

In numerous cases, we have already proved that the circulating water used for sludging has a two-fold effect on the field performance of a drill-rod: (*a*) an electro-chemical one *i.e.*, a corrosive one which, combined with the dynamic stresses, introduces stress-corrosion accelerating the progressive destruction of drill-rod — this is a detrimental effect; (*b*) a cooling effect of circulating water, which increases the endurance strength of the drill rod above the values obtained under dry conditions — this is a beneficial effect.

Cases (*a*) and (*b*) are illustrated in Figures 3 and 4 ref. 20), and particularly in Figure 3 (S.A.E. 1080) by curves *A* and *B* where, for stresses (loads) below the intersection point (*A-B*), the corrosive effect is detrimental; for stresses above point (*A-B*) the cooling effect of circulating water is a beneficial one, *i.e.*, it increases the life (time of drilling to failure) quite substantially. The same could be said about curves *C* and *D* in Figure 4 (Ni-Cr-Mo steel), curves *E* and *F*, and curves *G* and *H*.

In these four examples the beneficial water cooling effect for loads above the intersection points, and the detrimental effect of the stress corrosion below these intersections, is adequately illustrated. For stresses at the intersection points, these effects balance each other.

We do not have available data covering the steel mentioned by Mr. Troili (1.0% C, 1.0% Cr, and 0.30% Mo), but from the *S-N* relations for dry condition of that steel shown in Figure 14, ref. 19, we can assume with reasonable safety that similar relations exist.

Referring to Mr. Troili's observation "there is a tendency for the steel (drill rod) to break off a few inches from the bit end (at the so-called metallurgical notch)", we can offer the same explanations as given to Mr. Kemsley.

P. H. White, Works Manager, A. C. Wickman Limited, Toronto: I should like to make one comment. Whilst the improvement obtained through spiral rolling rods subjected to laboratory tests has not been entirely consistent on different types of test and with different steels, it is my impression that these results have nevertheless been more consistent, and have usually shown a somewhat higher degree of improvement, than with rods which have been spiral rolled in the field and then tested under production conditions. This is no doubt partly due to the difficulty in establishing properly controlled conditions in field testing and also of obtaining truly accurate reports. However, I am inclined to the belief that a major part of the disparity is due to the fact that some, at least, of the rods which have been spiral rolled in the field have not been spiral rolled under optimum conditions.

I therefore feel that it would be very desirable for Mr. Wlodek to publish a *Process Sheet* covering the recommended methods of spiral rolling and establishing tolerances wherever necessary. The following variables are some of those which I feel should be pinned down:

(1) Pitch of spiral in terms of thread per inch;

(2) Speed of rotation of rod in r.p.m.;

(3) Pressure on rollers in pounds;

(4) Radius required on top roller. Here I feel a tolerance is essential. Rollers should be manufactured close to the low limit and should be re-ground when they approach the high limit.

If different steels, or steels with different heat treatments, require different settings, these could readily be tabulated. If the above information were accompanied by a short general description of the process, I feel it would be very valuable.

Author's Reply: Regarding the comment by Mr. White, the descrepancy of results obtained on drill steel tested in our laboratory drilling machines as compared to results obtained in actual mine drilling could be reduced by selecting stress levels and the severity of water-corrosion conditions comparable to those existing in mining operations.

A proposed *S.R. Process Sheet* covering the recommended standard of S.R. is in preparation and should provide desirable data for the interested mining industry.

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