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FORGEABILITY OF STEELS: A Critical Survey of the Literature.

by

G. P. Contractor* and W. A. Morgan**

ABSTRACT

The use of low and high alloy steels is expanding considerably. The fabrication procedures for such alloys are becoming more complex. An attempt is made, in this report, to describe the effect of alloying elements on the hot-workability aspect of the fabrication of steels, and to indicate how changes in the forgeability characteristics may be predicted by laboratory tests. The different types of tests used and their limitations are discussed. Work which may be done to extend the use of these laboratory tests and to obtain more consistent and reliable results is outlined. A comprehensive list of references and a series of illustrative graphs complete the report.

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CONTENTS

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LIST OF ILLUSTRATIONS

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1. INTRODUCTION

The subject of forgeability#, or hot-workability, of iron and steel has interested many investigators, especially during the past 50 years. Iron and steel have been forged for several thousand years, but the operation has not always been successful, because of the cracking of the metal under hammer blows. With the addition of various alloying elements in recent years, the red-, or hot-, shortness of steels has increased. The stainless steels, for instance, have shown great susceptibility to cracking when forged or rolled at elevated temperatures. In other words, while many metals and alloys can be

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#In forging hammer practice, the term "forgeability" has often been defined as the reduction resulting from a blow of given energy.

easily altered from a given section into a desired shape by forging with either open or closed dies, there are alloys which present great difficulties even in such a simple process as upsetting. Furthermore, the performance of a material during forging not only depends upon its chemical composition, but is also dependent upon grain size, surface condition, range of forging temperature, and speed of deformation.

Various attempts have been made in the past to develop a device to determine whether a steel could be hot-worked and at what temperature it has the best forgeability. Nearly all conventional mechanical testing methods have been employed by one or more investigators[1, 2, 37] to evaluate certain of the metal characteristics which comprise forgeability. These are the compression, tension, bend, torsion and impact tests. These attempts have met with varying degrees of success. The purpose of this report is to give a brief preliminary survey of some of the work done on the evaluation of hot-working characteristics of metals, with emphasis on the results of the "hot-twist test" used in recent years by Ihrig[3, 4], Clerk and Russ[5, 6], and others[7, 8].

Although our knowledge of the behaviour of metals at elevated temperatures has increased considerably during the past several years, it is generally believed that most of the investigations have been carried out at proposed operating temperatures of equipment, rather than at processing or fabricating temperatures. The study has, however,

1. References are at the end of the report.

brought out an outstanding observation, which holds good for the entire high temperature range; that is, that the rate of deformation to which the metal is subjected is as important as the operating temperature itself. For instance, in low carbon steel (0.15% C) the rupturing temperature under the rates of deformation met with in creep tests, say of the order of 1 per cent per 10,000 or 100,000 hr, is less than 800°F, while in the rupture tests of 1,000 hr or more it is about 900°F. On the other hand, under the rates of deformation associated with tensile tests this temperature is around 1500°F. Since the rates of deformation usually encountered in forging and other hot-processing operations are greater than those applied in tensile strength measurements, it follows that the rupturing temperature for the same steel under these conditions would be much above 1500°F. It is generally believed[6] that the failure to appreciate this basic fact with regard to the influence of the rate of deformation has been responsible for the slow development of a successful device to determine the hot-working temperatures of metals.

2. LABORATORY TESTS FOR FORGEABILITY

2.1. Compression Tests

The usual earlier method for evaluating the ductility of forging stock was to heat cylindrical or square samples at different temperatures, draw them from the heating chambers, and forge them on a cold anvil with a cold hammer. It is generally known that many alloys will develop cracks along the periphery of a barrel-shaped forging if the reduction exceeds certain values. Examination of flattened samples for cracks gave a qualitative measure of the ductility component of forgeability.

Robin[9] was one of the early investigators to determine what he called the resistance of steels to crushing at various temperatures. He conducted tests on a number of alloys, both ferrous and non-ferrous, at temperatures which ranged from -300°F to 2010°F (-185°C to 1100°C). From the results of these tests, published in 1910, he was able to estimate the energy required to reduce normal* cylinders of these materials by 20 per cent of their original height. The resistance to crushing of carbon steels was found to be very considerable at liquid air temperatures, but diminished very rapidly up to zero, and then slowly up to 570°F, where the minimum resistance was found. Beyond 570°F (300°C) the resistance increased, and reached a maximum at about 930°F (500°C), followed by a rapid drop at 1560°F (850°C) and a very slow fall at higher temperatures. Figure 1 shows Robin's representative curves demonstrating the relationship between temperature and resistance to crushing of carbon steels. They bring out

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*Cylinders whose heights and diameters are equal.

clearly the well-known fact that the higher the carbon content of a steel the greater is its resistance to crushing or, in other words, the less is its forgeability, other things being equal.

Robin also investigated alloy steels and concluded that the resistance to crushing may be greatly reduced, or even obliterated, by the presence of a sufficient amount of an element in solution, such as, for example, chromium. He also noted that some steels preserve a high degree of resistance to crushing at high temperatures, a resistance much greater than that of carbon steels. The presence of nickel was reported to favour this resistance at elevated temperatures. The effects of chromium and nickel may, of course, be differentiated when it is considered that chromium forms complex carbides and nickel is an austenite former.

Since the publication of Robin's classical work in 1910, many important contributions have been made on the subject of forgeability of steels. Yensen[10] in 1920 observed that pure iron-nickel alloys do not forge readily, if at all, at ordinary forging temperatures and that manganese and titanium have the ability to strengthen the so-called "amorphous material" between the crystals to such an extent as to make it stronger than the crystalline matrix. He further recorded that aluminium, carbon, magnesium and silicon have little or no effect on the forgeability and that an examination of the microstructure gives no definite indication as to whether a material will forge well. It will be indicated later, however, that austenite is more difficult to forge than ferrite and that duplex structures do not forge as well as a homogeneous structure.

In 1924, Ellis[11] published a paper entitled "An Investigation into the Effect of Constitution on the Malleability of Steel at High Temperatures". This was one of the many papers[12-17] published by Ellis who has conducted numerous experiments on the forgeability of metals. The paper mentioned above dealt with the influence of the critical points in iron and steel upon their hot-working properties and showed that these points had significant effect in this connection. He pointed out that the atomic arrangement which occurs at the Ac_3 point appears to result in an increase in the resistance of iron to deformation. This is illustrated in Figure 2 which shows the forgeability-temperature relationship of practically pure iron over the range 1650-1740°F (900-950°C) within which lies the A_3 point.

The greater strength, or the resistance to deformation, of the gamma-iron phase above the critical points observed by Ellis may be explained by the fact that gamma-iron contains more carbon in solution than ferrite to strengthen the matrix.

To determine forgeability Ellis employed a method known as the dead-weight flattening test*. It consisted of measuring the percentage reduction in height of standard cylindrical specimens after being subjected to a blow, or blows, of a drop-forging hammer of given weight and falling freely from a fixed height. The test specimens were heated to a given temperature before being forged. The difference in height of the test specimen before and after forging, multiplied by 100,

*Also known as single-blow drop-hammer test, or impact compression test.

was referred to as the percentage reduction in height of the sample and was taken as a measure of forgeability of the material. Some of the forgeability-temperature curves obtained by Ellis on a group of steels are reproduced in Figures 3, 4, and 5. These curves are more or less similar in pattern but demonstrate that in the low-alloy steels studied, carbon has a greater effect than nickel or chromium.

Since the publication of Ellis' work a number of investigators[18-28] have employed a compression test for evaluating hot-malleability characteristics of metals by examining the development of cracks along the circumferential area of compressed barrel-shaped samples. This method has been applied to both hot and cold upsetting. It has been generally agreed that the reduction value at which ruptures begin to appear, or the maximum reduction which is obtained without fracture, should be used to determine the ductility component of forgeability. Thus, it has been suggested by Martin and Bieber[29] that the compression of nickel-alloys, for instance, from a 1-in. cube to 1/8 in. thickness, a reduction of about 87 per cent, represents the practical limit for this type of testing usually carried out at 1800°F and 2100°F. The ductility of a given alloy at a particular temperature is then obtained by subjecting a series of 1-in. cube specimens to blows of different energy, and noting the reduction at which cracking first occurs. In the case of nickel-alloys this procedure has been found useful for distinguishing between ductile and brittle (red-short) material at a given temperature, as illustrated in Figure 6.

In the case of other non-ferrous alloys, Portevin and Bastien[30] have shown that the compression test results are influenced by the forming speed. They indicated that as the speed of deformation is increased the temperature over which fracture takes place is markedly displaced toward high temperatures. In other words, cracks develop at a high strain rate up to a considerably higher forging temperature than at a low strain rate. This explains why, in hot-working light and ultra-light alloys, slow deformations are adopted (press forging, for example).

Investigators[31-34] have also tried to apply the compression test to copper-zinc alloys which offer forging and rolling difficulties in a certain range of composition, temperature, and speed of deformation. The results of these investigations have, however, failed to indicate any relationship between the compression test and the hot-shortness of such materials. Thus, it appears that the compression test could be of some value only where excessive hot-shortness is involved or where surface defects or contamination may lead to cracking after extensive upsetting.

In regard to the application of a compression test, it must be appreciated that the ductility of most materials is of a very high order under conditions where the strains are strictly compressive[35]. For instance, many materials considered unforgeable can be worked successfully by methods which utilize extrusion. On the other hand, as a cylindrical sample becomes barrel-shaped under the upsetting operation, associated tensile stresses come into play[36] around the periphery. It is these secondary tensile stresses which restrict the amount of compression and cause cracks to develop at the barrel-shaped surface. As the degree of barreling varies with the magnitude of the friction forces at the interfaces between the dies and specimen, it may be inferred that the ductility derived from a compression test also varies, depending upon the type of lubricant used.

Dietrich and Ansil[37] have shown (Figure 7) that the unit pressure required for cold upsetting a magnesium alloy increases considerably as the reduction approaches high values. This may be attributed to the rapid work hardening in this particular type of alloy. Of course, the frictional forces will increase when the pressure to cause deformation is increased, and the coefficient of friction of a cold-worked surface against the die may also increase, so it becomes practically impossible to cause further reduction beyond a certain limit.

Since 1950 excellent work has been carried out by Cook and his associates[26, 27, 28] in England on the hot-strength of a range of steels subjected to compression at temperatures varying between 1830°F and 2200°F, and at different rates of straining. Figure 8 shows the effect of straining of the compression stress of two alloy steels. It will be seen that the strength of steel at any given temperature is progressively increased by increasing strain rates. It is also clear that the effect of strain rate on the hot-strength is different for different materials. This obviously necessitates that the forgeability tests based on constant-rate compression technique must be carried out at rates comparable to those used in production. In fact, there appears to be no simple relationship between reduction obtained by impact compression (hammering) and reduction obtained by slow compression. In other words, static tests, performed at slow speeds, are likely to give a different rating of the steels from that obtained under conditions of rapid strain, such as in forging. They may either decrease or enhance certain features of forgeability observed at higher rates of straining.

Furthermore, it has been shown[28] that, in general, the soaking at the testing temperature reduces the hot-strength of the material, especially when it contains a carbide-forming element such as chromium. The presence of undissolved carbides in austenite has been put forward as an explanation for the higher strengths in steels when not soaked. However, as the testing temperature is increased, say from 1830°F to 2200°F, the difference between the strengths of rapidly heated and soaked samples is less marked. This has been attributed to the increased solubility of the carbides at the higher temperature and rapid grain coarsening. Another significant observation made by Cook and Blythe[28] has been that the time taken to heat up to testing temperature is a critical factor in hot-strength determinations when the specimens are not soaked.

A rough classification in respect to hot-strength of some of the steels studied by Cook is reproduced in Figure 9. It will be seen that the addition of alloying elements in increasing amounts has a tendency to make steels stronger at elevated temperatures.

In brief, it appears that although the compression test, either impact compression or constant-rate compression, has been employed to evaluate hot-working properties of steels, it has a number of uncontrolled variables and, unless they are reduced to the barest minimum, the method cannot be looked upon as a comparable qualitative measure of forgeability. Besides, if the procedure has to be a successful laboratory tool it should be simple, fairly quick, and correlatable with large-scale or commercial hot-working operations such as forging, rolling, piercing, etc. Another disadvantage of the compression test is the difficulty of maintaining the specimen at a constant temperature during the test.

2.2. Other Laboratory Tests for Forgeability

As mentioned previously, attempts have been made to evaluate the ductility of forging stock by tests other than compression. While these tests have proved useful for certain specific purposes, their general application to forgeability has been questioned by many investigators. There appears to be a definite lack of a simple forgeability test which would rate the materials in much the same manner as tension or fatigue tests. In this connection, Draper[38] has suggested that some test, designed after the bulging or expansion tests used to measure the ductility of plate, sheet or tube (at room temperature), may offer a solution to this problem. However, a hot-twist test in which the predominating stresses are in shear has received a good deal of attention in recent years as a means of evaluating hot-workability of metals.

2.3. Torsion or Hot-Twist Test

Sauveur[39] in his first Howe Memorial lecture in 1924 described the influence of carbon on torsional properties of steels near their critical points. He recorded that carbon increases the ductility (plasticity) of gamma iron. In the 1930 Campbell Memorial lecture, Sauveur[40] reported an investigation in which a twisting test of grooved bars was developed to determine some of the physical properties of carbon steels, austenitic and non-austenitic steels at temperatures under 1830°F (1000°C). The factor of stiffness obtained by dividing the torsional strength (breaking stress) in pounds by the number of twists to rupture (strain) brought out sharply the blue-heat range* in some steels (see Figure 12). Figures 10, 11 and 12 show some of the twisting test results on carbon steels obtained by Sauveur. He also demonstrated that the blue-heat brittleness range found in carbon steels was absent in the austenitic material and that red-shortness in plain carbon steels was essentially a property of face-centred (gamma) iron. It may be added that Sauveur's work was confined to the twisting tests carried out under 2000°F (1090°C) and, therefore, below the normal forging temperatures. Furthermore,

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*480-750°F (250-400°C), depending upon the carbon content.

he mentioned the existence of an apparent relationship between the creep stress* and the torsional strength determined by short twisting tests.

Since the publication of Sauveur's work[40] in 1930, torsion tests at elevated temperatures or hot-twist tests[41,42] have been considered by several investigators[3, 4, 5, 6, 7, 8] as one of the most suitable methods for measuring the forgeability of straight carbon and alloy steels. From the results on many steels, Clark and Russ[6] have concluded that hot-torsion tests indicate reliably the best temperature for hot-working. The number of twists to failure, when related to temperature, normally shows a maximum; the temperature at which it occurs is considered to be the optimum forging temperature.

In addition to the hot-twist characteristics, the test also gives torque measurements at various temperatures of testing. Whereas the number of twists to fracture is indicative of hot-ductility of the material, the torque is a relative measure of strength or flow stress. Although twist-temperature curves are of prime importance in determining the suitable forging temperature range, the torque curves are useful in indicating how the strength of material decreases as the temperature is increased. Figure 13 shows the temperature-torque relationship of carbon and alloy steels. It will be seen that 18Cr:8Ni stainless steel has the highest hot-strength at each of the temperatures examined, and that 0.16 per cent carbon steel has the lowest hot strength.

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*Creep stress for a life of 100,000 hr, with 1 per cent elongation.

2.4. Hot-Twist Test Apparatus

The apparatus has been described by Ihrig[3, 4], Clark and Russ[6], and by others, and in principle is similar to the one employed by Sauveur[40] over 25 years ago. It consists essentially of a furnace for heating and maintaining the specimen at a given temperature and a variable speed motor for twisting the specimen at the desired rate. A counter, which automatically starts and stops at the beginning and end of the test, gives the number of revolutions required for fracture. The determination of force during each test is obtained with the help of a weighing machine and a torque arm attached to one of the chucks mounted in a bearing[6]. Figure 14 shows the diagram of the apparatus employed by Ihrig[4].

2.5. Shape and Size of Test Bar

The test specimen employed by Clark[6] and Ihrig[4], a 22-24 inch long forged bar, had a diameter of about 9/16 in. throughout, with no central reduced section. As it is unlikely that deformation would be confined to the hottest (central) portion, the results from such a test specimen have been questioned by Hughes[8]. It means that the total twists to fracture include not only those resulting from twisting the specimen in the portion at the desired test temperature, but also those resulting from twisting in areas away from the hottest central section. The method, therefore, involves the twisting of a test specimen over a temperature range. As a result, the total number of twists may be affected by the length of the hottest zone in the furnace and the general temperature gradient existing throughout the specimen's length. This effect, of course, can be minimized by the use of a specially designed furnace.

Ihrig[3], on the other hand, found that there was no advantage in employing smaller or larger diameter bars than the 9/16 in. standard test specimens referred to earlier. He observed that reduced portions in the centre of the bars cause inaccuracies because the twists are not confined to the small central section, but show a tendency to pile up at the shoulders. Regarding the size of the rod, Ihrig's observations have been confirmed by Anderson and his associates[7], who found that the number of twists to failure is not greatly influenced by varying the diameter of the test specimens. They, however, did record that the number of revolutions required for rupture increased as the diameter of the test specimen was reduced from 5/8 in. to 3/8 in., as shown in Figure 15. It may be added here that in regard to the speed of testing, Anderson observed that as the rate of twisting increased, the number of twists to failure also increased, as indicated in Figure 16.

Furthermore, in spite of the objectionable features attributed to the use of the straight round test bar, Bloom and his co-workers[43] consider that the hot-twist test is valuable because it gives an approximate measure of the hot-workability (ductility) of materials at different temperatures. They employed the test to examine the relationship between the structure and hot-workability of stainless steel, and found that austenite and ferrite, when present together, apparently caused poorer workability than when only the predominant phase for a given alloy composition was present.

2.6. Temperature Forgeability Results

Figure 17 shows typical hot-workability curves[5] of four different steels, two of which represent the constructional types SAE 4615 and SAE 2512, one a high carbon tool steel and the other a stainless type 304 (18Cr:8Ni). These curves clearly indicate that in each case the number of revolutions required for fracture increases as the temperature is raised, until an optimum or a maximum temperature is reached, after which the number of twists decreases. These steels, however, bear out certain differences in (i) the number of twists required for fracture at a given temperature; (ii) the rate at which the number of twists required increases with temperature; (iii) the temperature at which the number of twists reaches a maximum; and (iv) the rate of decrease in the number of twists required after the optimum temperature is passed.

A comparison of the two constructional steels (Figure 17) indicates that whereas SAE 4615 has its temperature of maximum twist only about 25°F above that of SAE 2512, it approaches and departs from this temperature (2350°F) at a much slower rate, as shown by the slope of curve (1). The tool steel curve (3) is somewhat similar to SAE 2512, but its temperature of maximum twist is appreciably lower, being of the order of 2150°F against 2350°F for SAE 2512. On the other hand, 18Cr:8Ni stainless steel does not reach its temperature of maximum twist at 2450°F. However, this steel requires fewer twists for fracture than the other steels. It may be added here that extensive work in correlating the optimum temperatures obtained on the basis of twist tests, with well established forging temperatures on various grades of steels, has been carried out at the research and development laboratories of the Timken Roller Bearing Company, Canton, Ohio. As a result of this survey it was found that in general the optimum temperatures obtained from twist tests coincided with the maximum forging temperatures established through experience.

3. INFLUENCE OF ALLOYING ELEMENTS ON FORGEABILITY, AS DETERMINED BY LABORATORY TESTS

Although an extensive study of the effects of various factors, including the alloying elements, on the hot-workability of steels has been carried out by a number of workers, the published results of hot-twist tests by each investigator seem to be different from those of the others. In other words, hot-twist test data on even the same type of material do not appear to be comparable and/or reproducible. However, there are certain broad conclusions which can be drawn, on the basis of available information, to get a general idea of the effect of various alloying elements on the hot-workability of forging stock. In this connection it is important to mention[4], at the outset, that although the results of hot-twist tests on a single heat are very reproducible, the same reproducibility does not appear to exist between different heats of the same class of steels. This is clearly demonstrated in Figure 18 which shows tests on five heats of type 304 stainless steels. It will be noted that the temperature showing the maximum number of twists to fracture is different in each case and that there is quite a variation from one heat to another. In other words, it does not appear feasible to determine the maximum forging temperature from curves of single heats of various types of steel. Therefore, the best course, as suggested by Ihrig, is to obtain critical hot-workability data on individual heats in order to make them reproducible.

3.1. Carbon

Regarding the influence of carbon it has been observed that in the case of straight carbon steels containing under about 0.45 per cent carbon, the maximum ductility (workability) rises with increasing temperatures and that steels higher in carbon have their maximum ductilities at about 2350°F, or lower. Figure 19 shows the results reproduced graphically on five steels with carbon content varying between 0.04 and 0.96 per cent. It will be noted that the number of twists to fracture decreases at each temperature with increasing carbon content (especially in cases of high-carbon steels), as does the temperature at which the maximum number of twists takes place. This means that as the carbon content increases the ductility falls off rapidly with increase in temperature.

The general effect of temperature on 0.16 per cent carbon steel is shown in Figure 20. It clearly shows that above 2150°F, the ductility or hot-workability of low-carbon steel rises very rapidly.

3.2. Manganese

It is well recognized that manganese is essential in steels to reduce the red-short effect of sulphur. In general, it improves the forgeability of carbon steels as shown in Figure 21. However, in evaluating the influence of manganese it is important that the sulphur content of heats under comparison be as close as possible. This is essential because if the amount of sulphur in one heat is lower than in the other, less manganese will be utilized in neutralizing the adverse effect of sulphur and, therefore, its hot-workability will be comparable to that of the heat with higher manganese content.

Figure 21 also shows that 12 per cent manganese austenitic steel has very low hot-workability. This is not surprising, in view of the fact that the maximum number of twists to fracture of ferritic steels is greater than that of the austenitic material as demonstrated in Figure 22.

Studies of the effect of manganese on stainless steels of the types 304 and 321 have indicated that manganese above 0.40 per cent does not appear to improve the hot-workability of these steels. The consensus of opinion is that nickel and manganese tend to have the same or additive effect, so that in lower nickel steels it would be expected that manganese would be more effective. However, in the case of 304 (18Cr:8Ni) and 321 (18Cr:8Ni:Ti) types of stainless steel, the nickel content is already high, thus restraining the beneficial effect of manganese on the forgeability of these steels to a limit of about 0.40 per cent.

3.3. <u>Sulphur</u>

It is well known that presence of sulphur in relatively large amounts adversely affects the hot-workability of ferrous and non-ferrous materials. Figure 23 shows that when the amount of sulphur was 0.021 per cent in steel (1), the number of twists to fracture at 2100°F and 2350°F was about 170 and 320, respectively. However, when the sulphur content increased to 0.116 per cent, as in steel (3), the twists required for fracture were reduced to 70 and 110 at 2100°F and 2350°F, respectively. Steels (5) and (6) in Figure 23 also indicate that although manganese is important to counteract red-shortness produced by sulphur, the steel containing 0.014 per cent sulphur is apparently superior in terms of ductility at high temperatures.

Figure 24 further illustrates how the hot-working properties of low-carbon steels, with practically no manganese, are affected by the presence of even small amounts of sulphur. It will be noted that the maximum number of twists to fracture at 2000°F for steel (1) with 0.002 per cent sulphur is 440 as compared with only 40 for a similar steel (2), but with twice as much sulphur, i.e. 0.004 per cent.

Regarding the effect of sulphur on straight chromium stainless steels, there is some evidence to indicate that in steels of the types 410 (11.50-13.50% Cr) and 416* (12-14% Cr), chromium has a tendency to reduce the undesirable effect of sulphur so as to make these types of steel easily hot-workable. It must, of course, be borne in mind that these steels are ferritic even at the forging temperature.

3.4. Silicon

The effect of silicon on the forgeability of low-carbon steel is reported to be negligible if the amount is within 0.20 per cent. Above about 1.00 per cent the hot-workability appears to fall appreciably, as illustrated in Figure 25. However, these results must be taken with caution, like most of the published data on hot-twist tests, as the

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* Zr, Mo -- max. 0.60 per cent.

sulphur content of steels (3) and (4) is higher, and the amount of manganese lower, than in steels (1) and (2). Higher sulphur contents associated with relatively low manganese will have the added depressing effect on the forgeability of steels (3) and (4). Thus, it is difficult to determine whether the reduction in hot-ductility of steels (3) and (4) was due principally to high silicon content, or was a combined effect of high sulphur and high silicon. However, steel (4) with silicon as high as 1.20 per cent has certainly the lowest hot-workability in the temperature range of 2250°F to 2400°F.

Regarding the effect of silicon on high-alloy steels, there is some evidence to show that in the case of austenitic stainless material of the types 302 and 304 (18 Cr:8 Ni), the hot-workability is reduced at higher temperatures if this element is present in amounts greater than 0.5 per cent. This has been tentatively explained as due to the ferrite-forming tendency of silicon, which forms a duplex structure generally considered detrimental to the hot-workability of metals.

3.5 Nickel

Provided the nickel content is kept below 5 per cent it has, like manganese, a tendency to improve hot-twist characteristics of low-carbon steels, as shown in Figure 26. This figure shows that pure nickel is ductile at high temperatures, thus contributing favourably to the hot-working properties of steel. However, its presence in larger amounts seems to reduce the hot-workability as indicated by curve (4) in Figure 26. This reduction is attributed to the effect of nickel as a former of austenite. Curve (6) shows the hot-working properties of Monel and how the addition of copper in large percentages has a depressing effect on the forgeability of nickel and nickel-alloys.

3.6. Chromium and Other Alloying Elements

Chromium is an element which is present in small and large amounts in alloy steels. It is often associated with nickel, molybdenum, and silicon. Its general effect (Figure 27) in low-carbon steels is to reduce hot-workability of the material. However, published data tend to indicate that where it is present in excess of about 9.0 per cent the hot-twist characteristics improve, especially above 2300°F, as is borne out by curve (4), Figure 27. This effect, as shown earlier in Figure 22, could be attributed to the formation of a homogeneous ferrite matrix instead of a two-phase structure.

In straight high-chromium stainless steels the hot-workability decreases[4] with higher carbon content, and Figure 28 shows the effect in type 446* steel. On the other hand, in nickel-chromium steels of type 304** the low carbon material shows poorer hot-workability than does the material containing 0.07 and 0.08 per cent carbon, as illustrated in Figure 29. Although this behaviour has been attributed to the formation of delta iron in the lower carbon stainless steels (curves 1 and 2, Figure 29), it is questionable whether the difference

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* 23-27% Cr:1% Ni max.with 0.25% C max.

**18% Cr:8% Ni with 0.08% C max.

in the hot-twist characteristics of these steels is due to the variation in carbon content, or is due to the normal spread of heats as indicated in Figure 18.

It has been reported that in alloy steels, the alloy content of a given material, as well as its carbon content, influences the apparent hot-workability, and that the alloy content is of even greater significance in steels containing 1.00 per cent or more of carbon. This is demonstrated in Figure 30, which shows how the forgeability is depressed in high-carbon steels by the addition of elements such as molybdenum, tungsten, and chromium. Figure 31 further illustrates the effect of molybdenum in low-carbon steels of the composition SAE 1015. It shows that steels of the same carbon content but without molybdenum are superior in terms of hot-ductility. In the case of stainless steels of the type 18Cr:8Ni, the effect of molybdenum is also to lower the hot-workability as shown in curves (4) and (5), Figure 31. It is believed that molybdenum, which is a ferrite-forming element, gives rise to a second phase, thus lowering the hot-workability of this type of steel.

The hot-twist characteristics of various grades of austenitic stainless steel are reproduced in Figure 32. It will be seen that marked differences exist in the hot-workability of these steels and that the addition of stabilizing elements such as titanium or columbium appears to decrease both the temperature of maximum twist and the number of twists at this temperature. Similarly, increasing the chromium and nickel contents, as in 25Cr:12Ni and 25Cr:20Ni steel (curves 5 and 6,

Figure 32), lowers the number of revolutions required for fracture. Furthermore, curve (4) indicates clearly that the forgeability of 18Cr:8Ni steel is considerably lowered by a higher percentage of sulphur. In fact, steel (4), Figure 32, shows the poorest performance.

3.7. Lead, Tin, and Nitrogen

Lead, like sulphur, has been used in recent years to improve the machinability of steels. Nitrogen has been employed as an alloying element in chromium steels to stabilize austenite at normal temperatures. It is also found as an impurity in all commercial steels. In straight carbon and low-alloy steels, the amounts normally present are small and not harmful to the hot-workability. However, in the high chromium steels the ductility is adversely affected at high temperatures with increase in nitrogen content. Tin is not used as an alloying element but is often found in modern steels as an impurity. The effect of these elements on the hot-working properties of steel is not favourable. They seem to have a depressing effect as shown in Figures 33 and 34. For reasons of comparison, heats with low and high sulphur are also included in Figure 34. It will be seen that the effects of tin and lead are very similar to that of sulphur, the curves (2) and (4) being fairly close to the high-sulphur steel curve (6).

It has been reported that oxygen, phosphorus, cobalt, vanadium and titanium individually have little, if any, effect on the hot-forgeability of steels, provided they are present in normal amounts. It will be of interest to determine the effects of vanadium in quantities of about 1 per cent. For instance, low carbon steels with phosphorus content varying between 0.013 per cent and 0.025 per cent show little difference in their hot-workability curves (see Figure 35). On the other hand, steels with even small differences in sulphur content have markedly different hot-twist characteristics, as shown earlier in Figures 23 and 24.

4. SUMMARY AND CONCLUSIONS

1. Nearly all conventional mechanical testing procedures have been tried by one or more investigators to determine metal characteristics which comprise hot-workability or forgeability. These attempts have met with varying degrees of success.

2. There appears to be a definite lack of a simple forgeability test which would rate materials in much the same manner as does the tension or the fatigue test.

3. In recent years the hot-twist test, in which the predominating stresses are in shear, has been accepted as the best technique for measuring the hot-working properties of steels at different temperatures.

4. The method consists in twisting test specimens at a series of controlled temperatures; the temperature that allows the maximum number of turns before failure is taken as the most suitable temperature for hot-working.

5. It has been found that the maximum number of twists to fracture occurs at the temperature that has been known in practice to be best, or optimum, for the rotary piercing of steel rounds or billets in the production of seamless tubings. The optimum temperature also appears to be a satisfactory temperature to use in assessing the forgeability of steels.

6. The hot-twist test data so far published have been mostly on steels of various compositions, no attempt having been made to apply this test to non-ferrous material.

7. It is not feasible to assess the relation of the available results from hot-twist testswith practical shop experience in various hot-working operations, some of which are less severe than others. It is, therefore, essential that due consideration should be given in correlating the published data with the particular type of hot-working process involved.

8. In certain operations, such as piercing, for instance, the temperature rises during processing and in such cases adjustment of the operating temperature is necessary so that after the temperature rise the maximum or optimum temperature does not exceed the temperature of maximum twist to fracture.

9. One of the most significant and discouraging aspects of the hot-twist test is that, whereas the results on a single heat are reproducible, the same reproducibility is absent between different heats of the same class of steels. In other words, to determine the hot-workability of steels the test must be conducted on individual heats.

10. The results of various investigators on the same type of material do not compare favourably, the forgeability-temperature curves obtained by one investigator being very different in shape from those of another. These variations, of course, may be minimized by closer control of (a) the rate of heating to, and time at, the forging temperature, and (b) the rate of strain.

11. The variation in results from heat to heat appears to be more pronounced the higher the total alloy content of the steel. It is

believed that this difference is a function of the material being tested rather than the test itself, which is generally accepted as a very suitable laboratory tool for measuring the hot-working properties of metals.

12. Most of the published results were obtained on rolled or forged material. It is, therefore, questionable whether these results could be comparable to those of the same material when in the as-cast or ingot condition.

13. Since hot-working operations in steel processing begin initially on the ingot, it is important that a comparative study of the hot-twist characteristics of rolled or forged products versus similar cast materials should be undertaken in the future.

14. Most of the published results have been obtained on straight round test bars (22 in. long x 1/2 in. dia.) without having a reduced section in the centre. The results from such a test specimen have been criticized in certain quarters and have been considered of little significance.

15. In spite of the objectionable features of the test bar, the consensus of opinion is that the hot-twist test is valuable in evaluating approximately the hot-working properties of steels at different temperatures.

16. With regard to the speed of testing, it has been reported that as the rate of twisting increases, the number of revolutions to rupture increases.

17. Although the size of the test bar does not seem to make a significant change in the number of twists to fracture, there is evidence to show that as the diameter of the specimen decreases from 5/8 in. to 3/8 in. the number of revolutions required for fracture increases.

18. The microstructure of the steel does not give any definite indication as to whether it will forge well, except when it is possible to distinguish a duplex and single phase structure.

19. The test does not appear to yield any useful information about the effect of surface defects on the hot-working properties of steels, although it is known, in practice, that many hot-processing troubles are associated with defects of this kind. This aspect appears to merit further work.

20. A good deal of interesting work has been done to determine the influence of alloying elements on the hot-workability of steels. However, there appears to be a large scope for a systematic study of the effect of elements individually and in combinations on the hot-working properties of known and unfamiliar steels.

21. Briefly, the influence of alloying elements is as follows:

i) Free-machining additions such as sulphur or selenium decrease both the temperature of maximum twist and the number of twists at this temperature. In other words, these elements depress the hot-workability of steels.

ii) The effect of tin or lead is strikingly similar to that of sulphur.

iii) The strong carbide-forming elements such as titanium or columbium have a tendency to reduce the forgeability of the austenitic chromium-nickel steels at higher temperatures (above 2300°F).

iv) The ferrite-forming elements, e.g. silicon and molybdenum, adversely affect the hot-workability of steels, especially in austenitic chrome, nickel stainless steels at higher temperatures. The same adverse affect is increasingly seen in low-carbon steels if these elements are present in excess of about 0.20 per cent.

v) Chromium produces a deleterious effect up to about 9 per cent in low-carbon steels, and above this amount it appears to improve the hot-workability, especially around 2300°F.

vi) Nickel and manganese, in general, improve the hot-workability of carbon steels. However, when these elements are present in large amounts the workability is affected by the formation of austenite. Hot-twist tests have clearly demonstrated that manganese counteracts the red-short effect of sulphur.

vii) Nitrogen has a marked depressing effect on the hot-working properties of higher chromium steels of the types 430 and 446, probably due to its austenite stabilizing tendencies. In carbon and low-alloy steels the amounts normally present are small, and these quantities do not affect the ductility at high temperatures.

viii) The effect of phosphorus, vanadium, cobalt, and oxygen is not precisely known. However, these elements, when present individually in small normal amounts, do not appear to have a significant effect on the hot-workability of steels.

ix) The austenitic steels, such as types 304 (18Cr:8Ni) and 12 per cent Mn, show lower hot-workability than ferritic straight chromium steels of the type 410. Likewise, increasing the chromium and nickel contents, as in type 309 (25Cr:12Ni) or 310 (25Cr:20Ni) steel, lowers the number of maximum twists to fracture, i.e. hot-workability.

x) The austenitic steels with ferrite-forming elements, such as titanium or molybdenum, or with insufficient austenite-forming elements, such as nickel or manganese, tend to develop duplex structures which have the poorest hot-working properties.

22. The test appears to be a useful tool (a) to find the effect of composition and constitution on hot-workability; (b) to indicate the best hot-working temperature for steel and how critical this temperature is; and (c) to compare the hot-workability of a newly developed or unfamiliar steel with one whose hot-twist characteristics are already worked out, by comparing the optimum number of twists to rupture.

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6. ILLUSTRATIONS APPENDIX

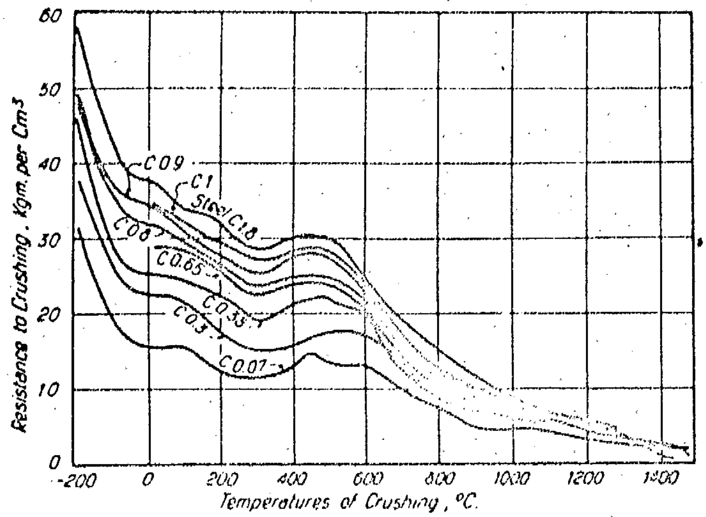


Fig. 1. - Resistance of carbon steels to crushing.
(After: F. Robins, ref. 9)

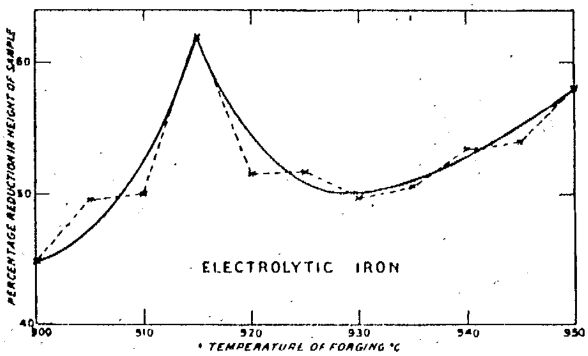


Fig. 2. - Relation between forgeability and temperature
for electrolytic iron.
(After: O. W. Ellis, ref. 17)

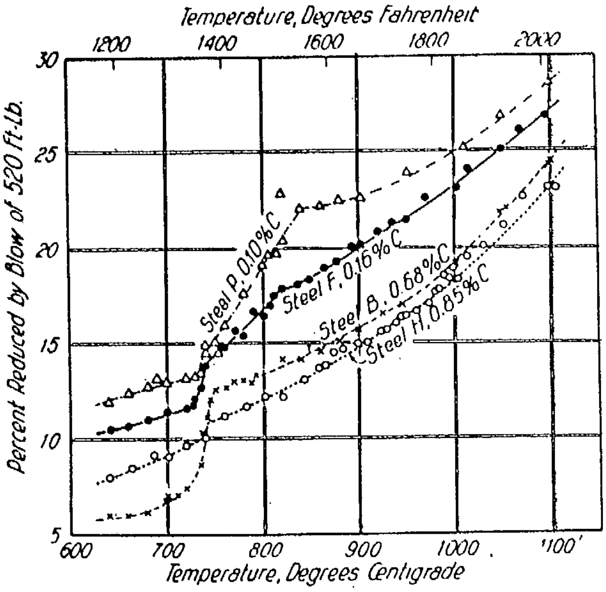


Fig. 3. - Effect of carbon on forgeability of carbon steels. (After: O. W. Ellis, ref. 17)

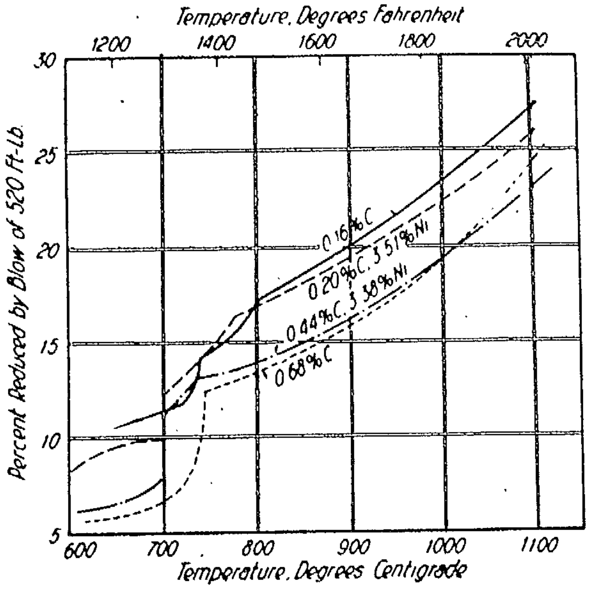


Fig. 4. - Effect of nickel on forgeability of carbon steels. (After: O. W. Ellis, ref. 17)

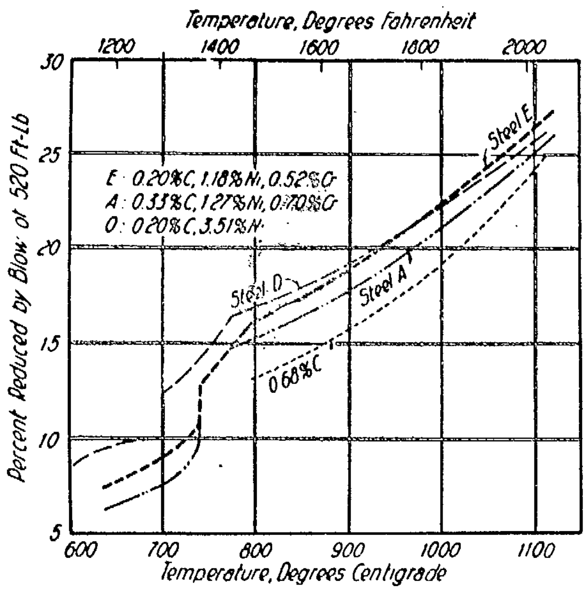


Fig. 5. - Relative forgeability of a nickel steel and two nickel-chromium steels. (After: O. W. Ellis, ref. 17)

Fig. 6. - Compression tests of 1800°F and 2100°F on malleable heat (left) and hot-short heat (right) of Ni alloys.
(After: L. H. Martin and L. O. Bieber, ref. 29)

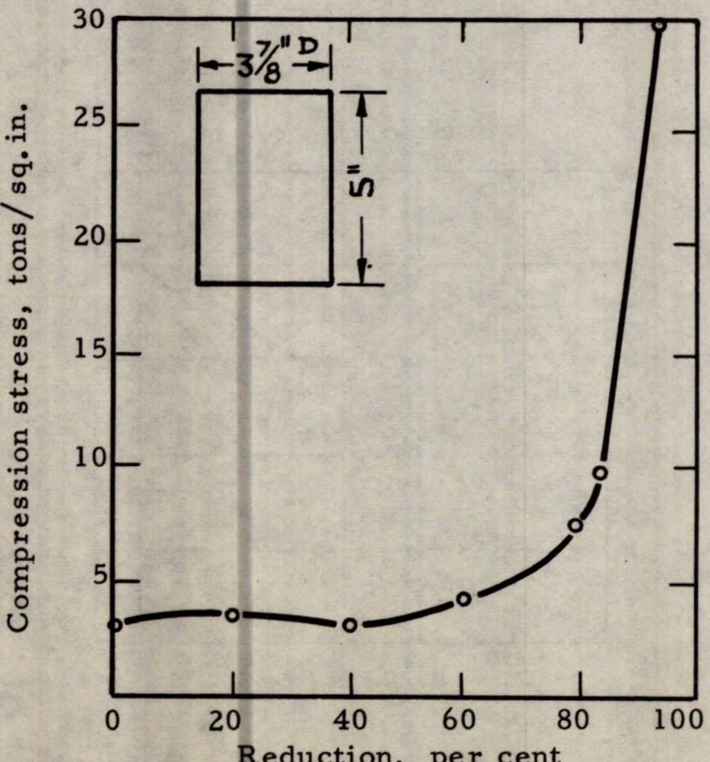


Fig. 7. - Compression-reduction curve for a magnesium alloy up to high reductions.
(After: Dietrich and Ansil, ref. 37)

Composition, per cent

	Steel A	Steel B
Carbon	0.47	1.06
Manganese	0.58	0.46
Silicon	3.74	0.22
Chromium	8.20	1.41
Nickel	0.20	0.17
Sulphur		0.019
Phosphorus		0.031

* Strain rate—in./in./sec.
(Testing temperature, 1830°F)

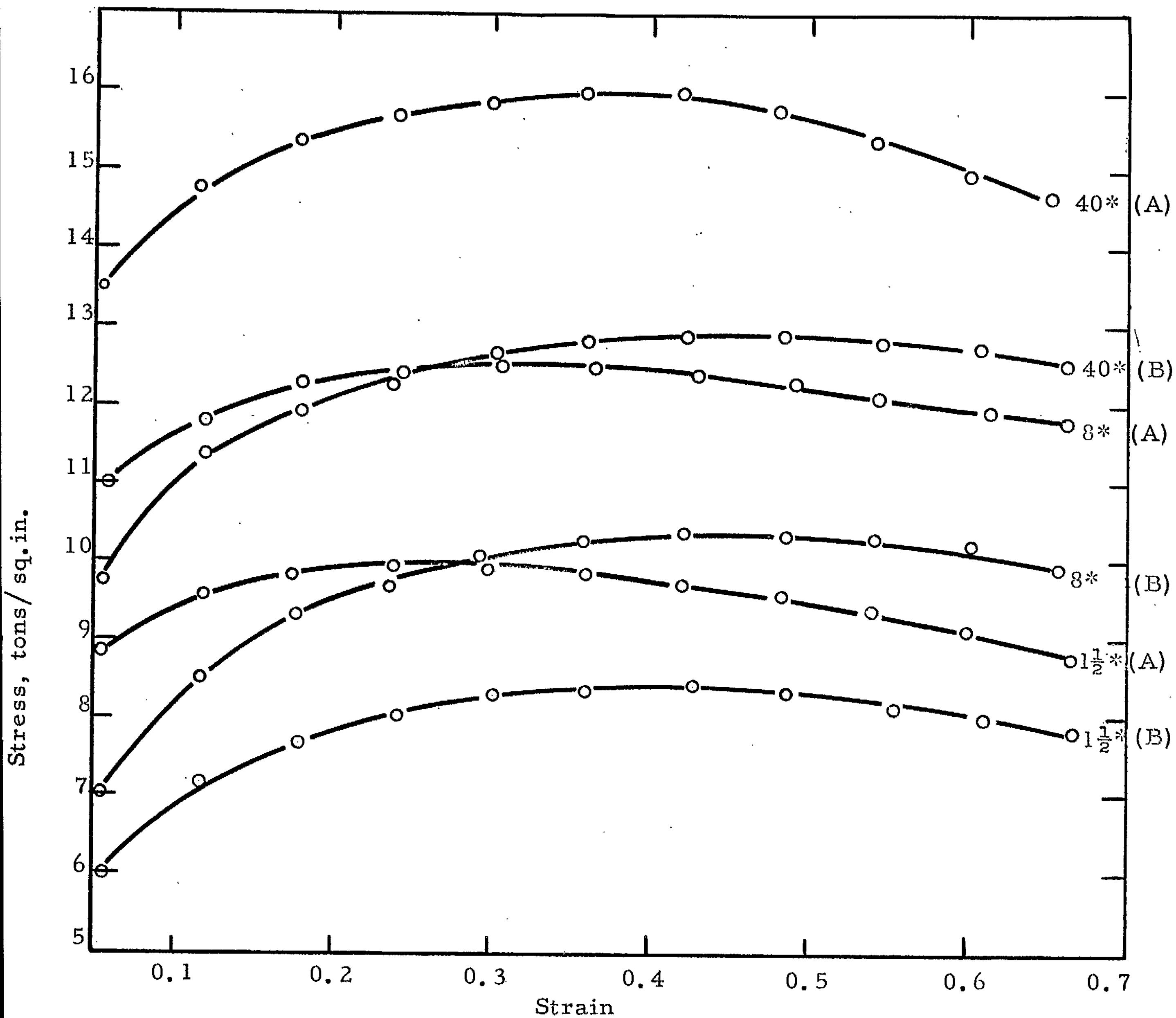


Fig. 8. - Compression stress-strain curves showing effect of strain rate on compression stress for two steels at 1830°F.
(After: P. M. Cook and A. J. Blythe, ref. 27, 28)

	Composition, per cent							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Carbon	2.23	0.47	0.26	0.35	0.61	0.35	0.17	1.06
Manganese	0.37	0.58	0.57	0.66	0.94	1.49	0.62	0.46
Silicon	0.43	3.74	0.36	0.27	1.58	0.27	0.153	0.22
Chromium	13.10	8.20	3.03	0.59	0.12	0.03		1.41
Nickel	0.33	0.20	0.29	2.45	0.27	0.11		0.17
Molybdenum			0.49	0.59	0.06	0.28		
Sulphur			0.009	0.023	0.038	0.041	0.054	0.019
Phosphorus			0.023	0.029	0.035	0.037	0.032	0.031

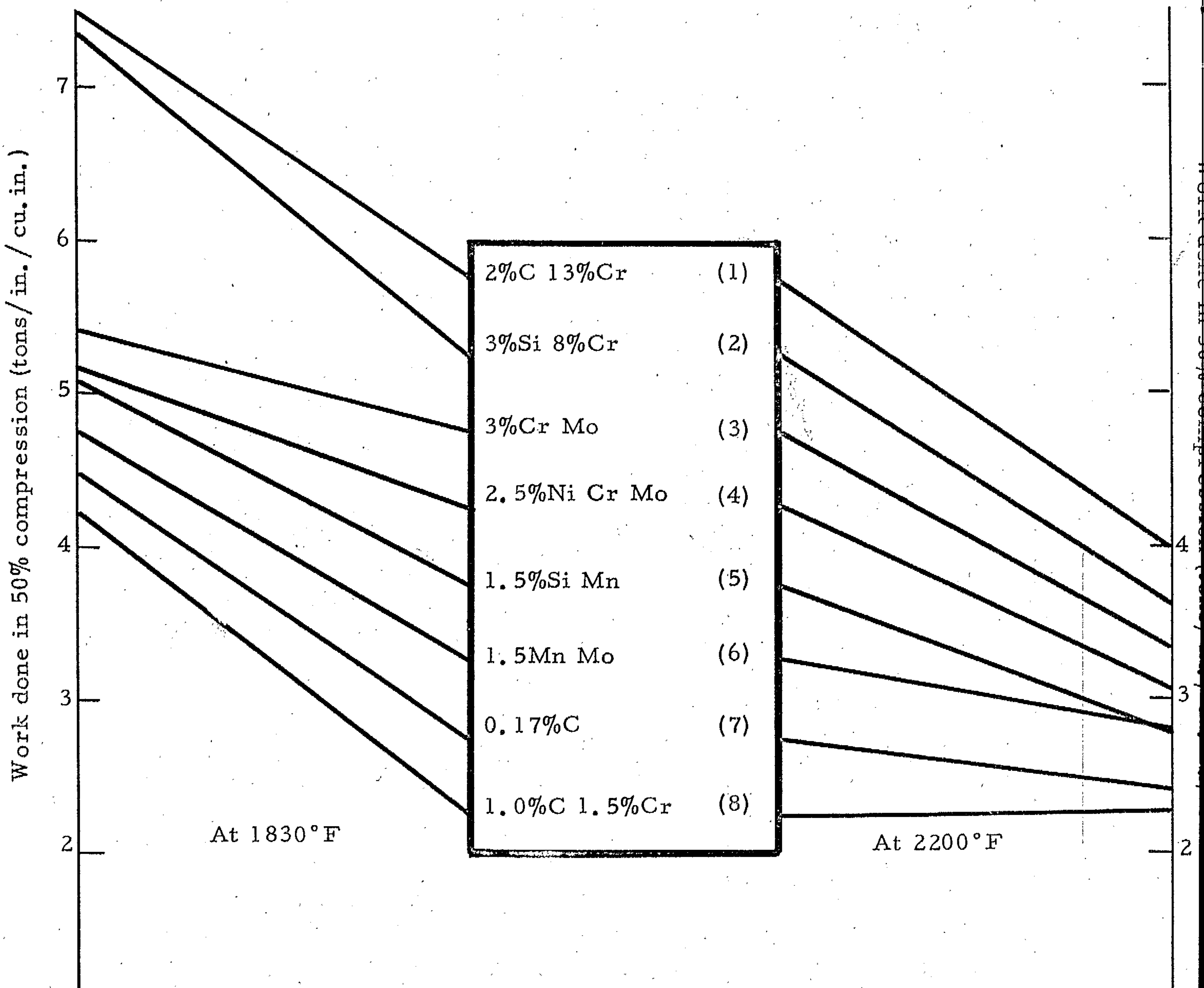


Fig. 9. - Relative strengths of steels in compression at 1830°F and 2200°F.
Strain rate: $1\frac{1}{2}$ in./in./sec.
(After: P. M. Cook and A. J. Blythe, ref. 27, 28)

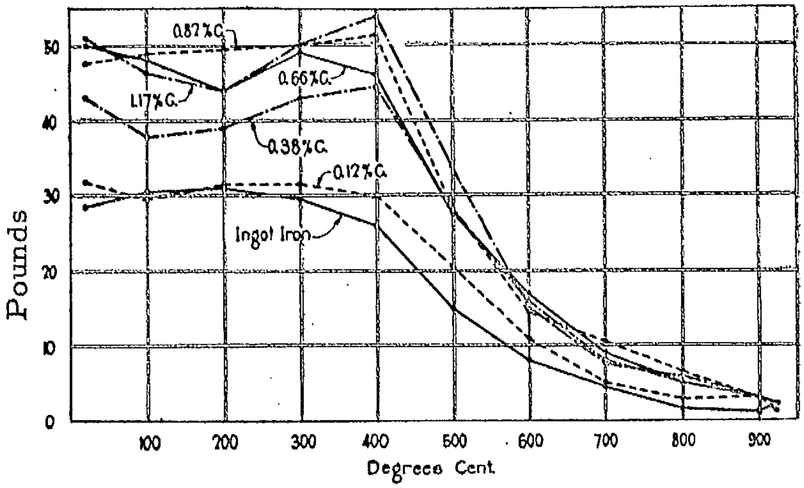


Fig. 10. - Torsional strength of ingot iron and of some carbon steels at various temperatures. (After: A. Sauveur, ref. 40)

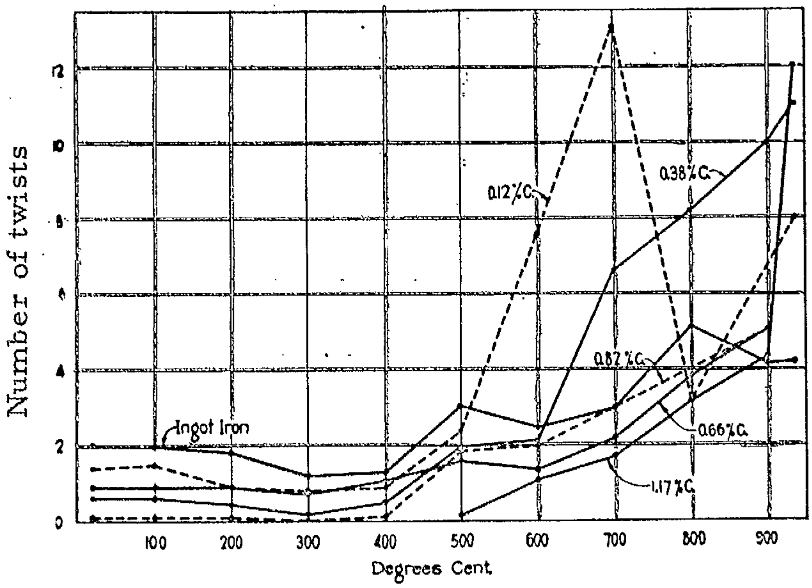


Fig. 11. - Twist of ingot iron and of some carbon steels at various temperatures. (After: A. Sauveur, ref. 40)

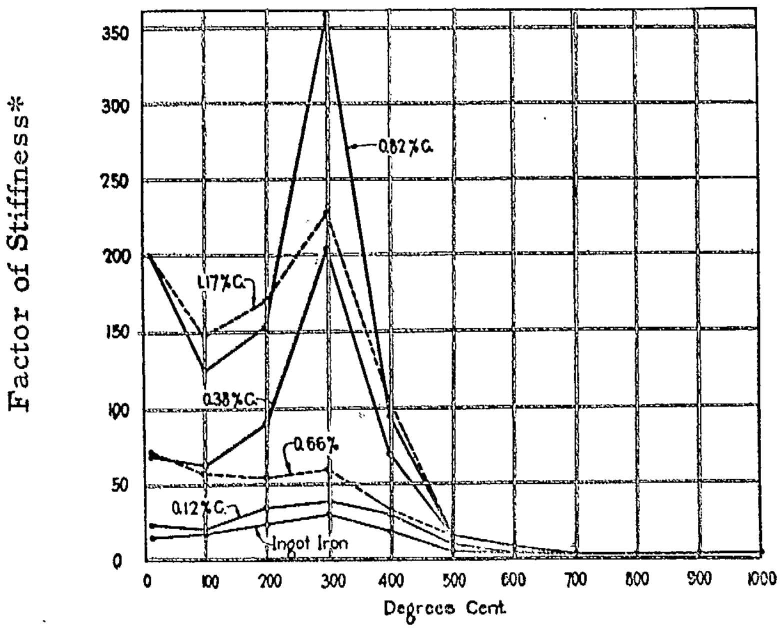
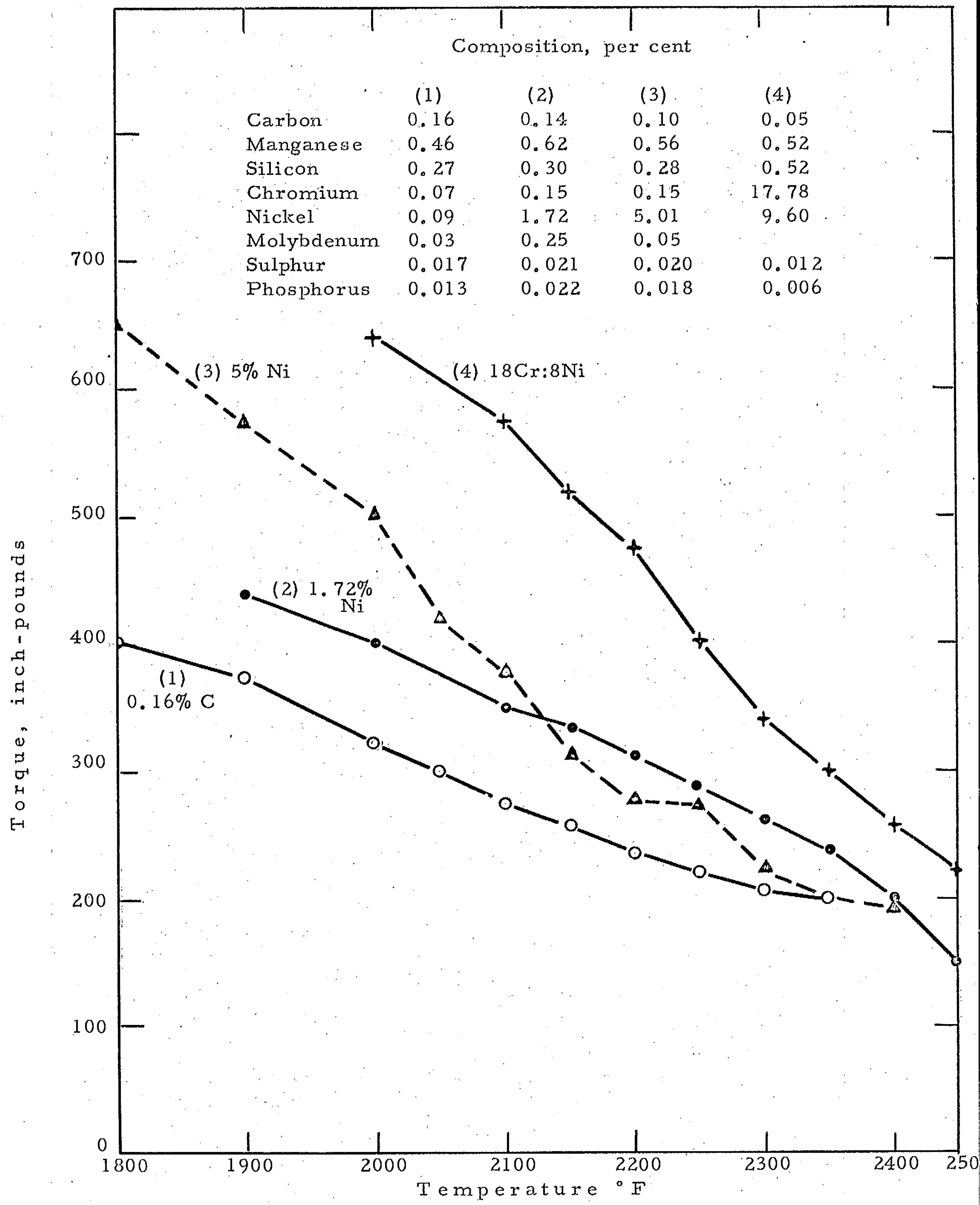


Fig. 12. - Factor of stiffness * of ingot iron and of some carbon steels at various temperatures. (After: A. Sauveur, ref. 40)

*Ratio of torsional strength (breaking stress) to number of twists to failure (strain).



	(1)	(2)	(3)	(4)
Carbon	0.16	0.14	0.10	0.05
Manganese	0.46	0.62	0.56	0.52
Silicon	0.27	0.30	0.28	0.52
Chromium	0.07	0.15	0.15	17.78
Nickel	0.09	1.72	5.01	9.60
Molybdenum	0.03	0.25	0.05	
Sulphur	0.017	0.021	0.020	0.012
Phosphorus	0.013	0.022	0.018	0.006

Fig. 13. - Torque characteristics of some steels.

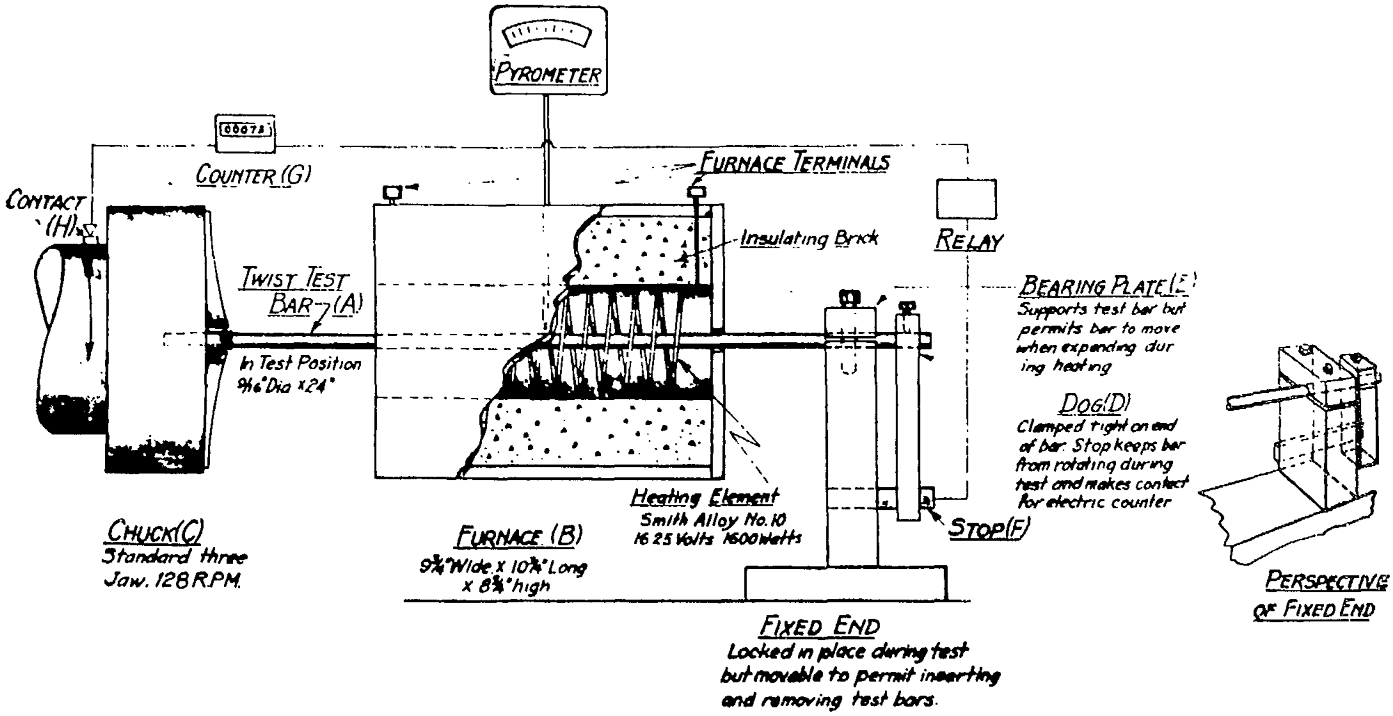


Fig. 14. - Hot-twist test apparatus employed by Ihrig (ref. 4) to determine forgeability of steels.

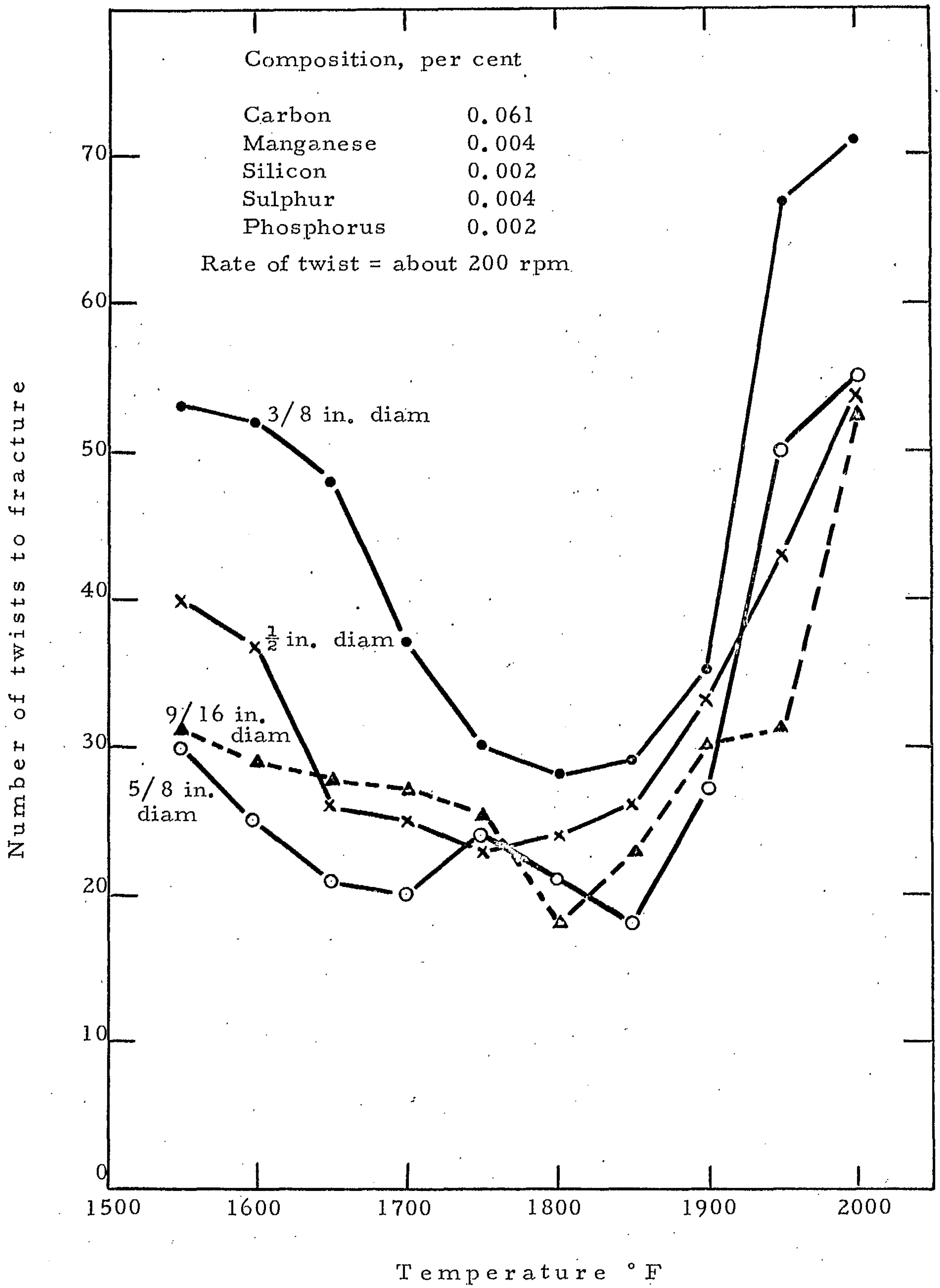


Fig. 15. - Influence of test bar diameters on hot-twist characteristics of low-carbon steels.
(After: C. T. Anderson et al., ref. 7)

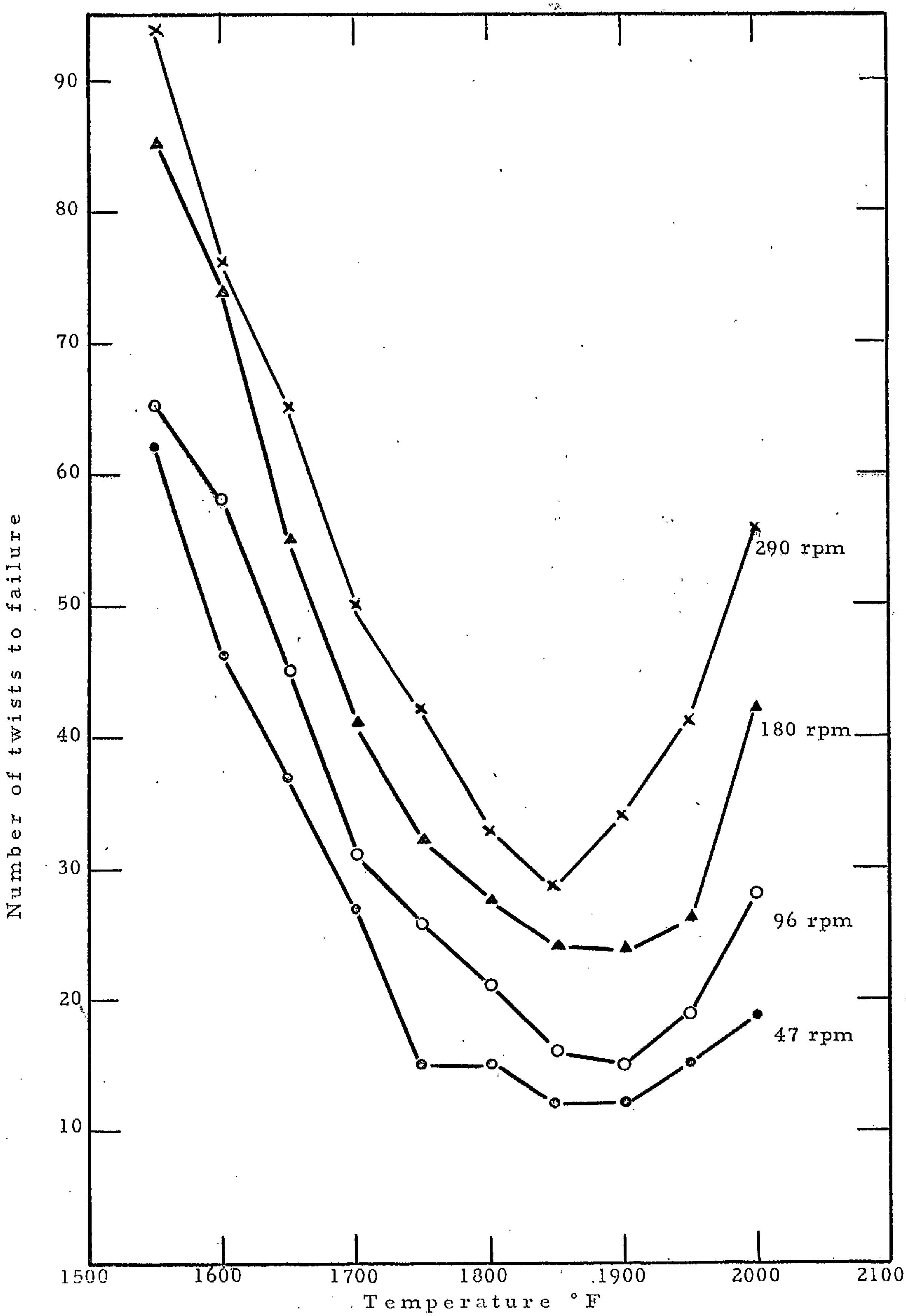


Fig. 16. - Influence of rate of deformation on hot-twist characteristics of low-carbon steel bar, 3/8 in. diam.
(After: C. T. Anderson et al., ref. 7)

Composition, per cent

	(1)	(2)	(3)	(4)
C	0.14	0.10	1.02	0.05
Mn	0.62	0.56	0.31	0.52
Si	0.30	0.28	0.35	0.52
Cr	0.15	0.15	0.30	17.78
Ni	1.72	5.01	0.09	9.60
Mo	0.25	0.05	0.03	-
S	0.021	0.020	0.018	0.012
P	0.022	0.018	0.015	0.006

Arrow indicates maximum recommended forging temperature.

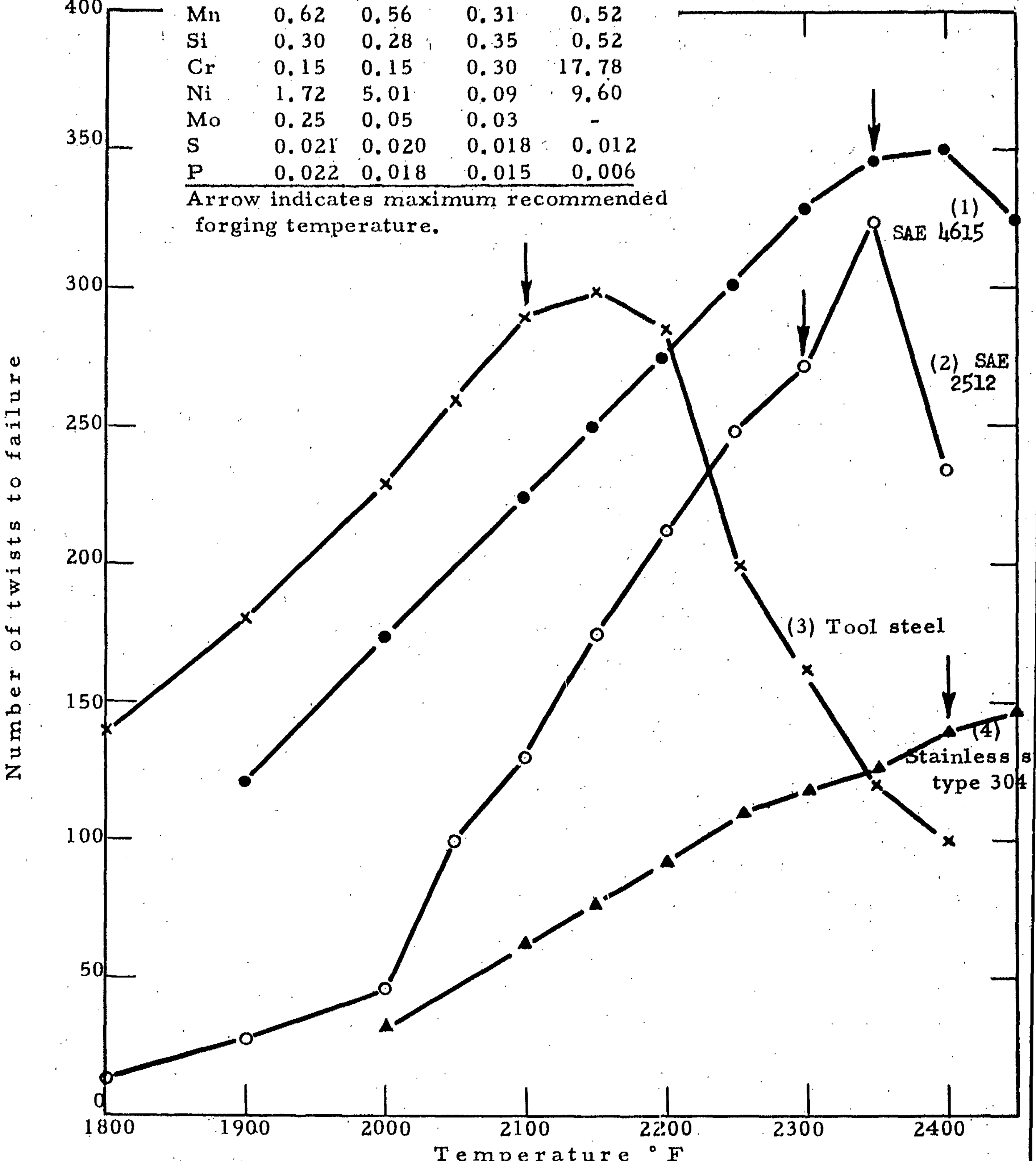


Fig. 17. - Typical hot-workability curves of four different steels. (After: C. L. Clark, ref. 5)

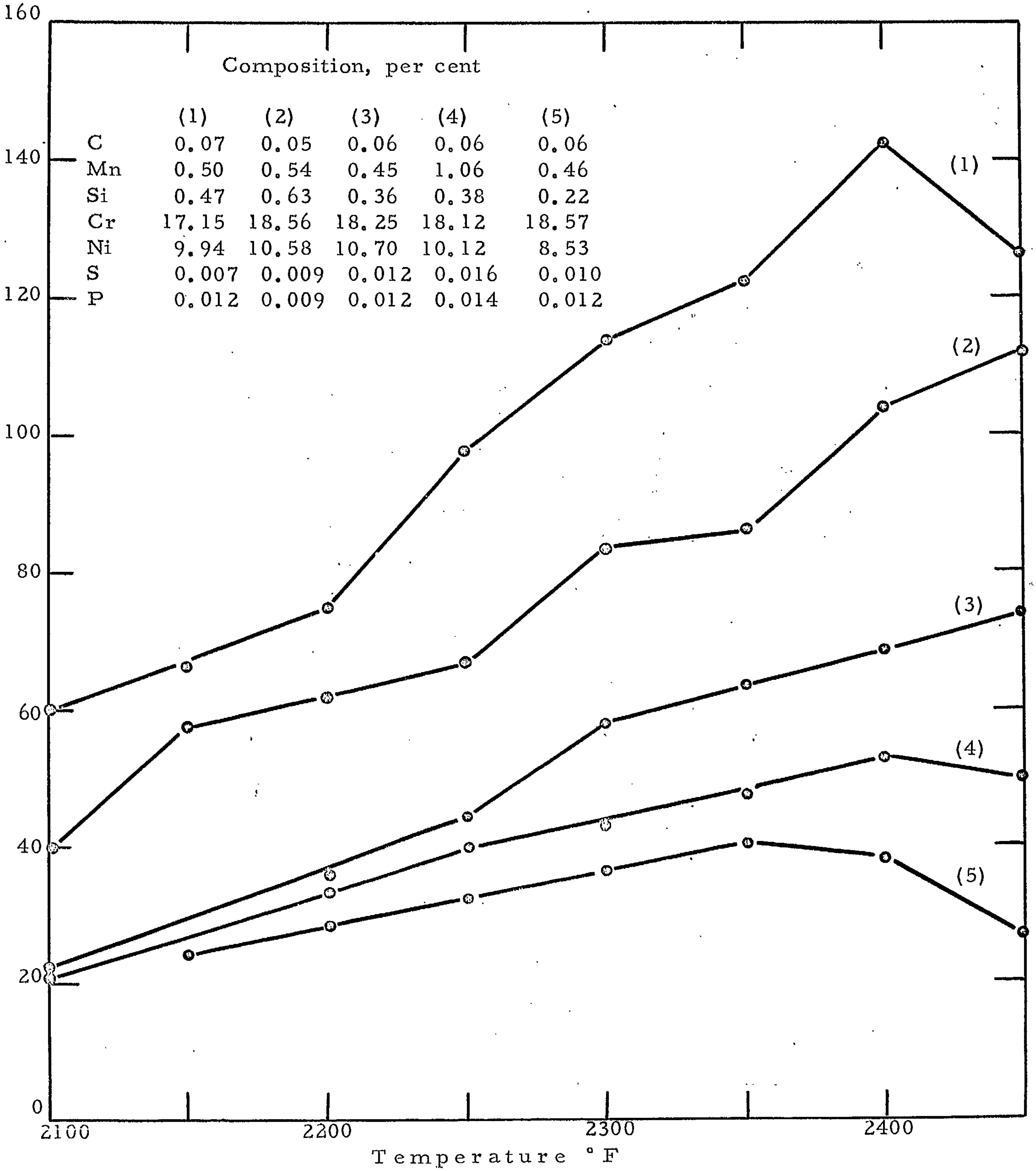


Fig. 18. - Curves showing spread of hot-twist test data on the same class of steel (stainless type 304), but representing different heats.
(After: H. K. Ihrig, ref. 4)

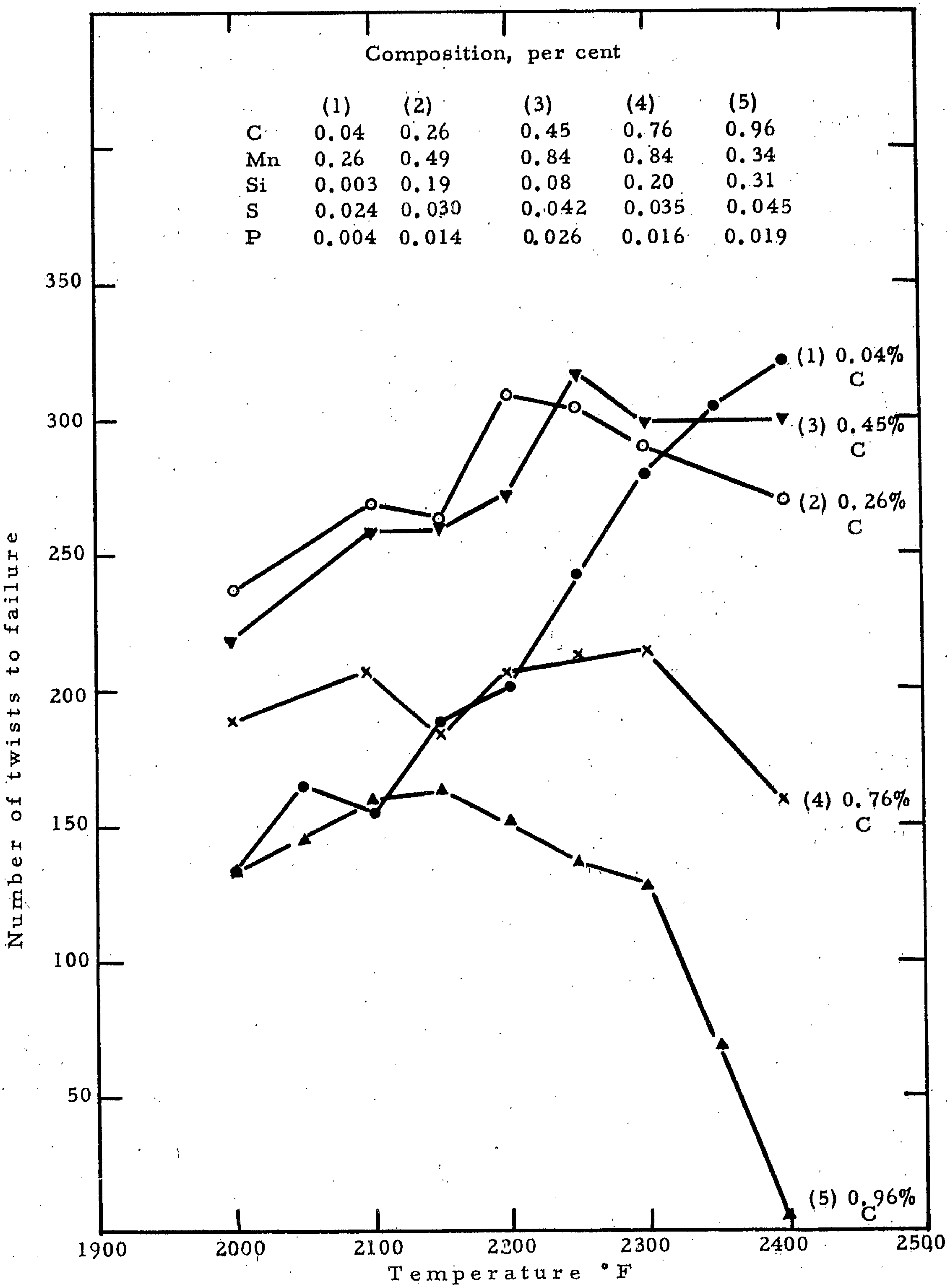


Fig. 19. - Effect of carbon on hot-workability of straight carbon steels. (After: H. K. Ihrig, ref. 4)

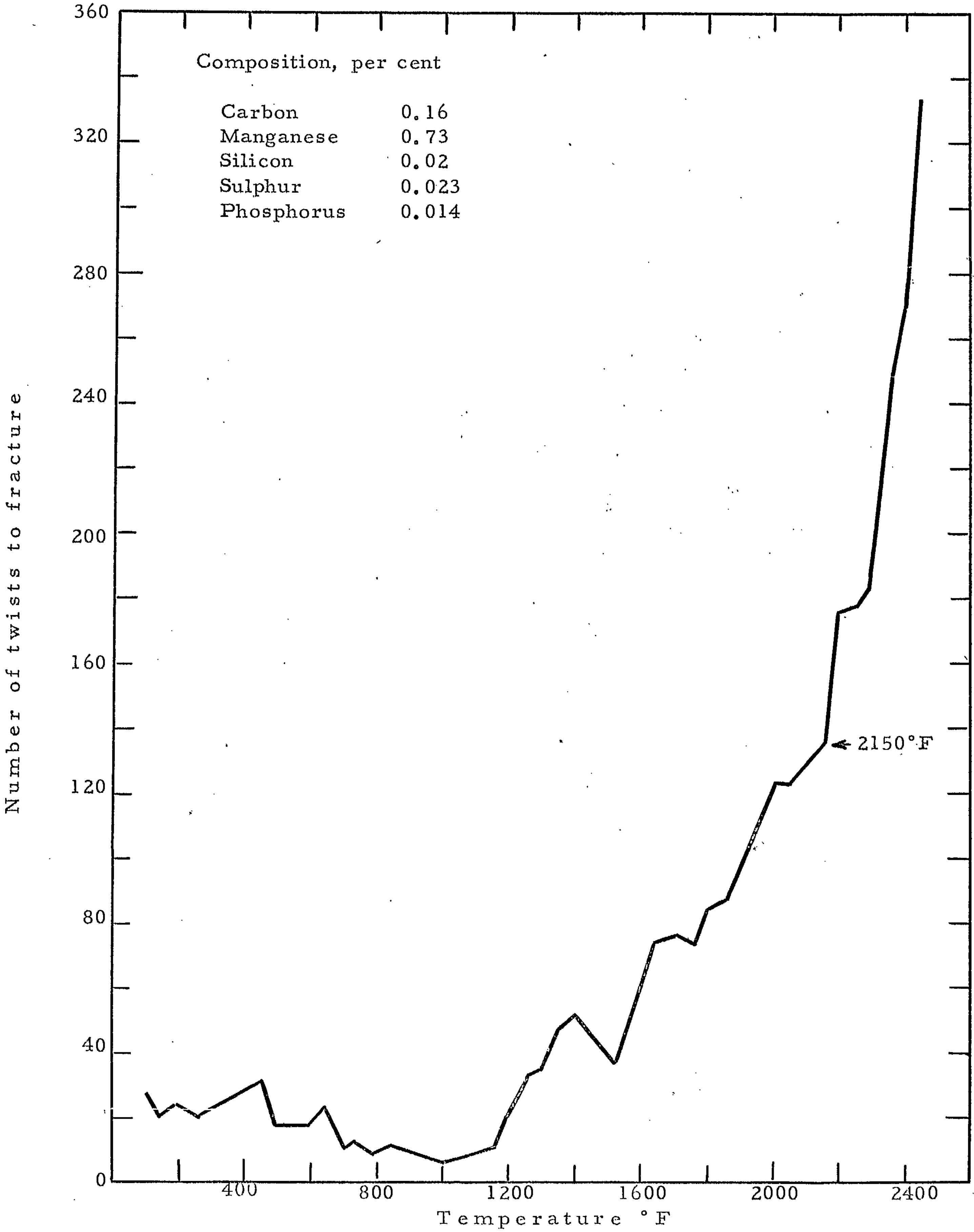


Fig. 20. - Effect of temperature on hot-workability of 0.16% carbon steel. (After: H. K. Ihrig, ref. 4)

Composition, per cent

	(1)	(2)	(3)	(4)	(5)
C	0.02	0.04	0.22	0.26	0.64
Mn	0.005	0.26	0.45	1.05	12.88
Si	0.02	0.003	0.08	0.23	0.88
Ni					3.11
S	0.026	0.024	0.021	0.028	0.032
P	0.009	0.004	0.014	0.021	0.017

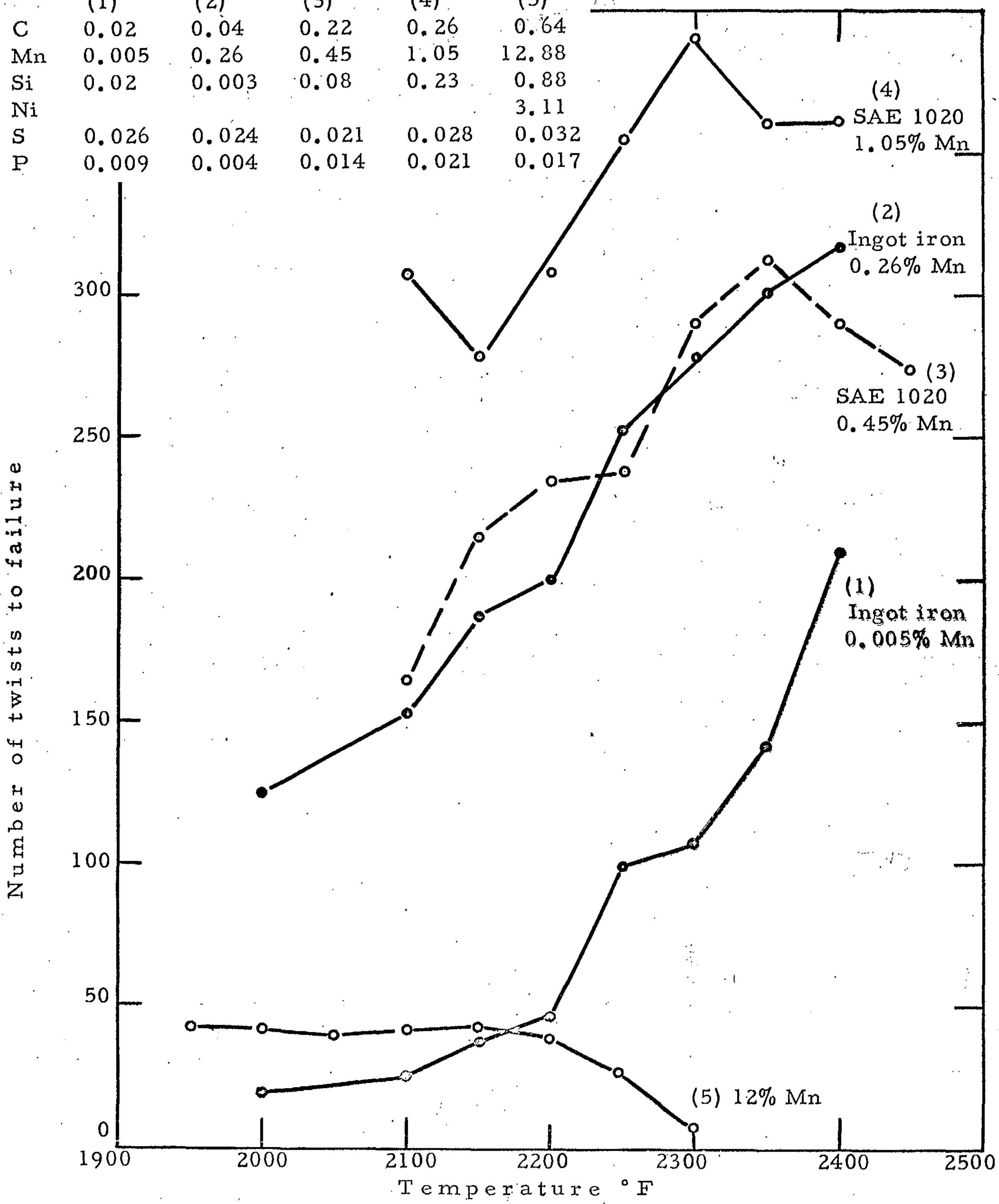
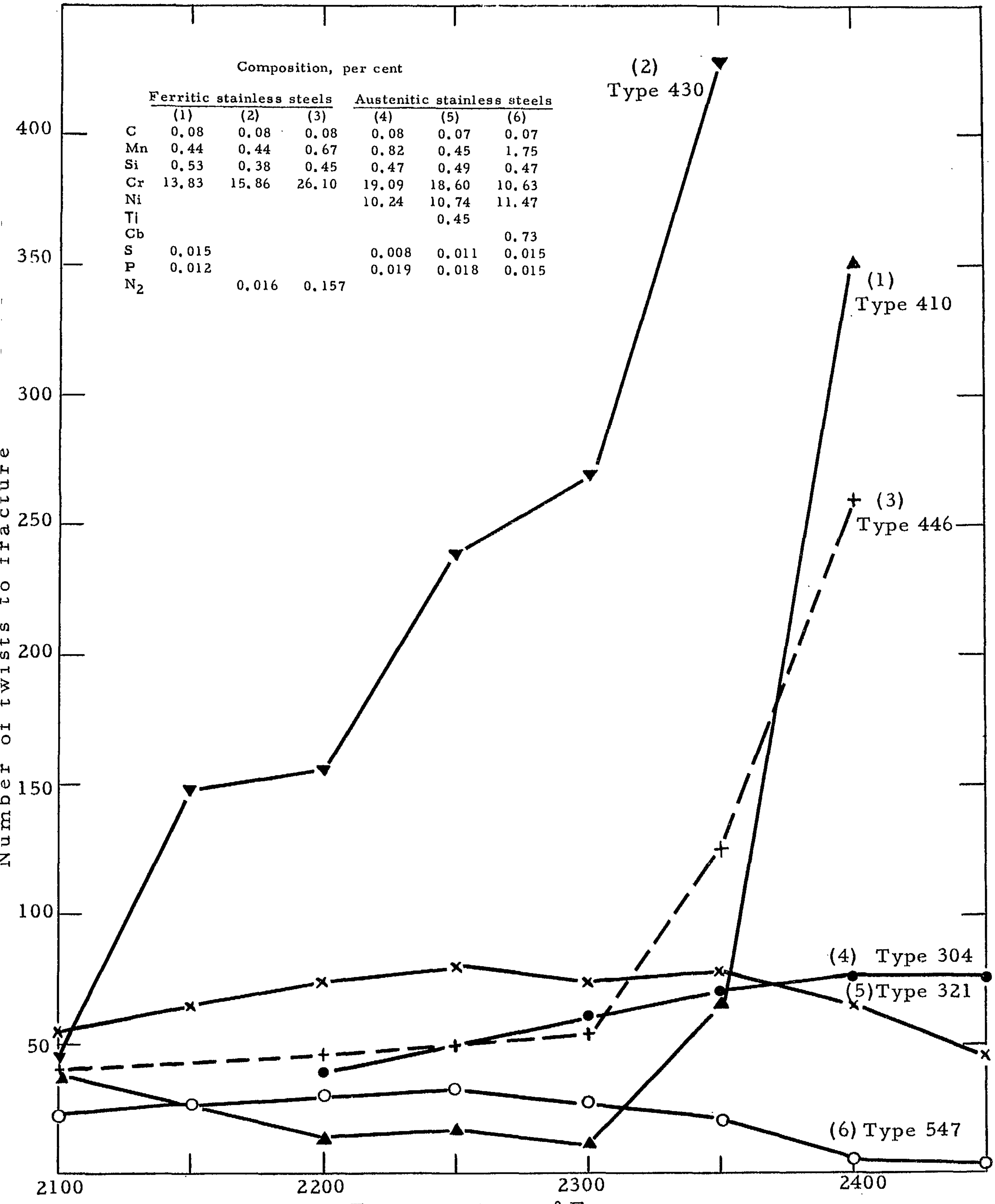


Fig. 21. - Effect of manganese on hot-workability of low-carbon steel. (After: H. K. Ihrig, ref. 4)



Composition, per cent

	Ferritic stainless steels			Austenitic stainless steels		
	(1)	(2)	(3)	(4)	(5)	(6)
C	0.08	0.08	0.08	0.08	0.07	0.07
Mn	0.44	0.44	0.67	0.82	0.45	1.75
Si	0.53	0.38	0.45	0.47	0.49	0.47
Cr	13.83	15.86	26.10	19.09	18.60	10.63
Ni				10.24	10.74	11.47
Ti					0.45	
Cb						0.73
S	0.015			0.008	0.011	0.015
P	0.012			0.019	0.018	0.015
N_2		0.016	0.157			

Fig. 22. - Comparison of hot-workability of austenitic and ferritic stainless steels. (After: H. K. Ihrig, ref. 4)

Composition, per cent

	(1)*	(2)	(3)	(4)	(5)	(6)
		SAE 1020			SAE 1335	
C	0.22	0.22	0.24	0.24	0.36	0.33
Mn	0.45	0.48	0.46	0.44	1.74	1.62
Si	0.08	0.08	0.08	0.08	0.27	0.20
S	0.021	0.052	0.116	0.130	0.014	0.12
P	0.014	0.014	0.014	0.014	0.014	0.026

* (1) represents the original heat i.e., ladle analysis; Heats (2), (3), and (4) represent resulphurized ingots of (1).

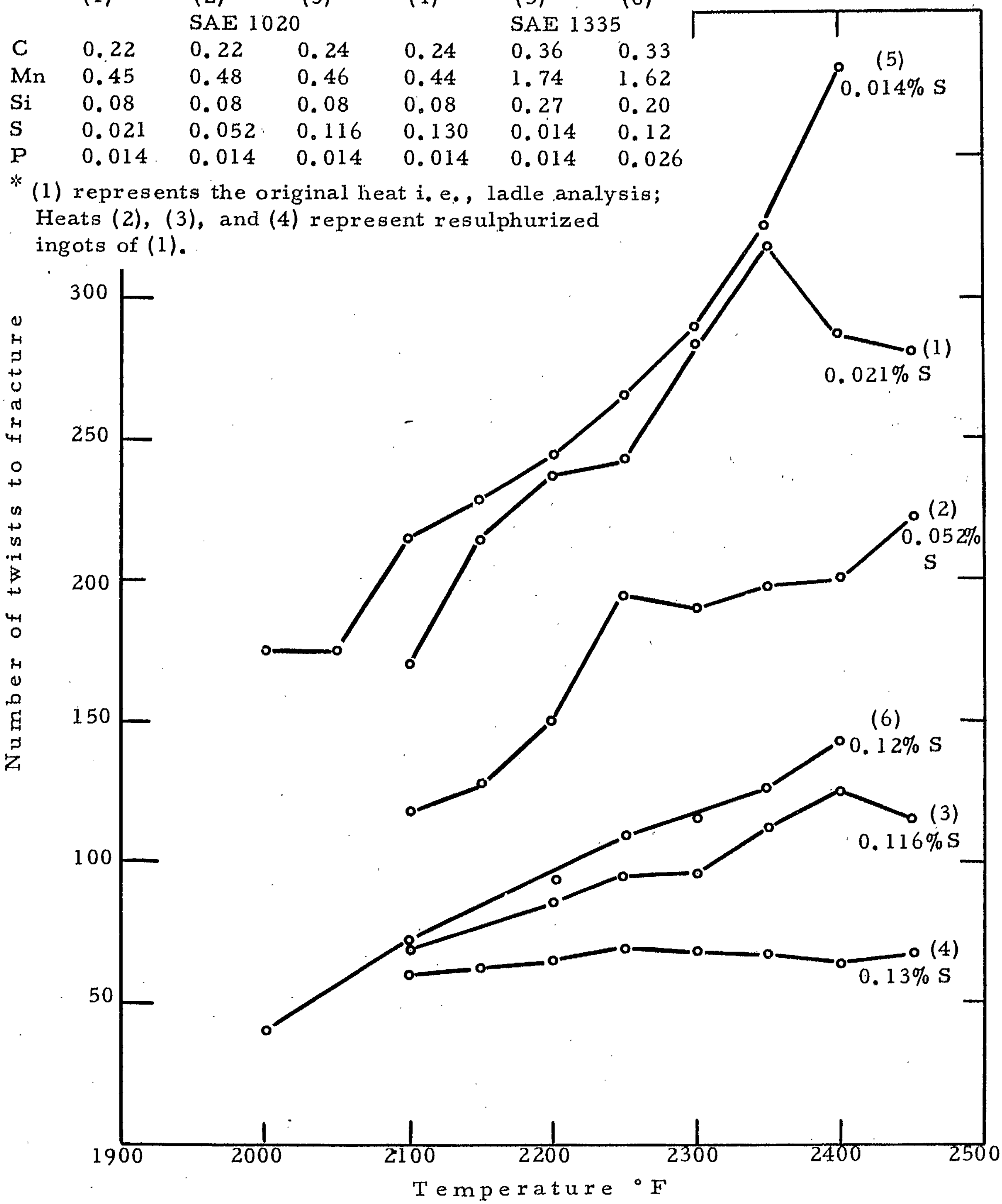


Fig. 23. - Effect of sulphur on hot-workability of carbon steels. (After: H. K. Ihrig, ref, 4)

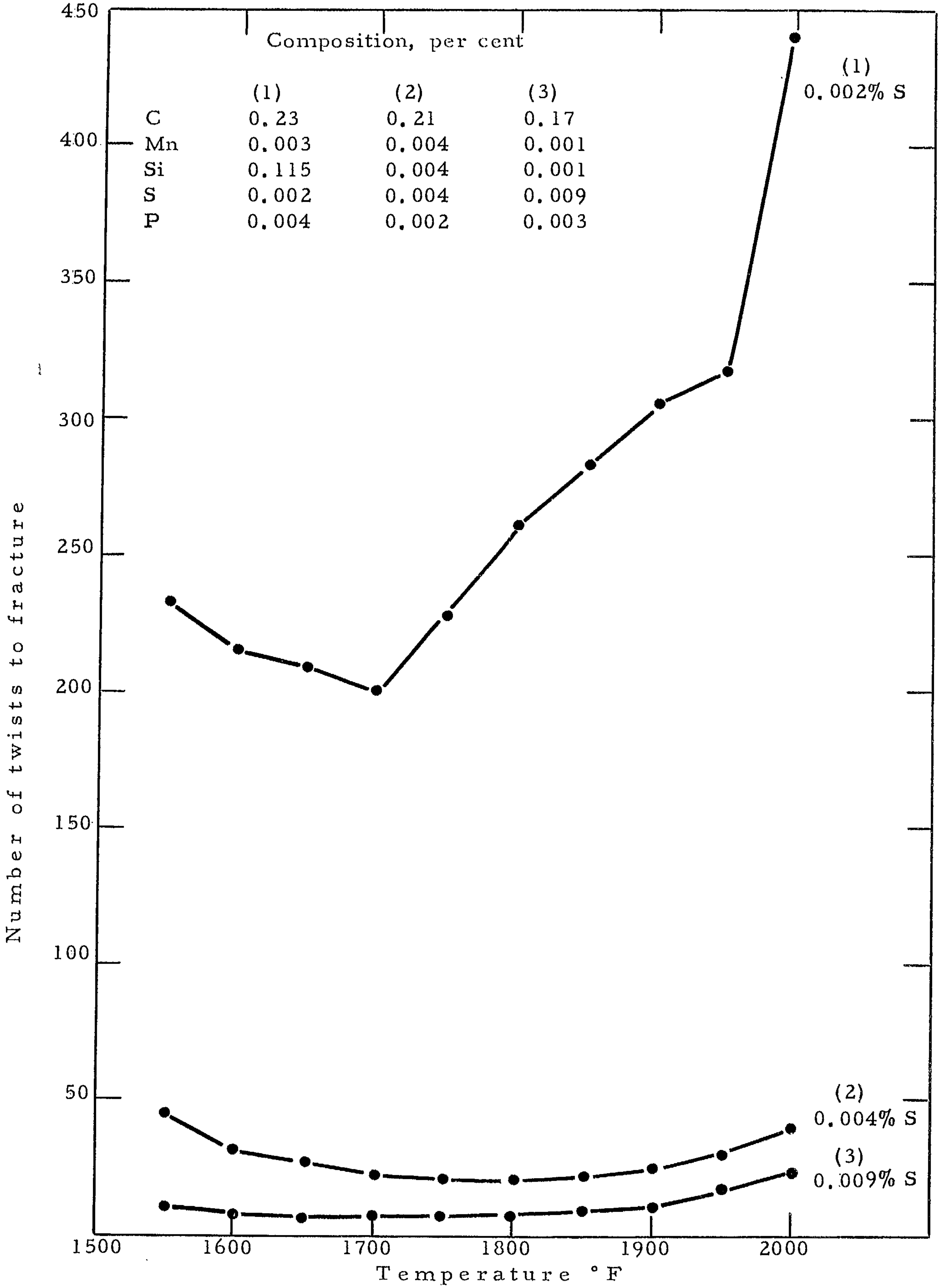


Fig. 24. - Effect of sulphur on the hot-workability of low-carbon steel. (After: C. T. Anderson et al., ref. 7)

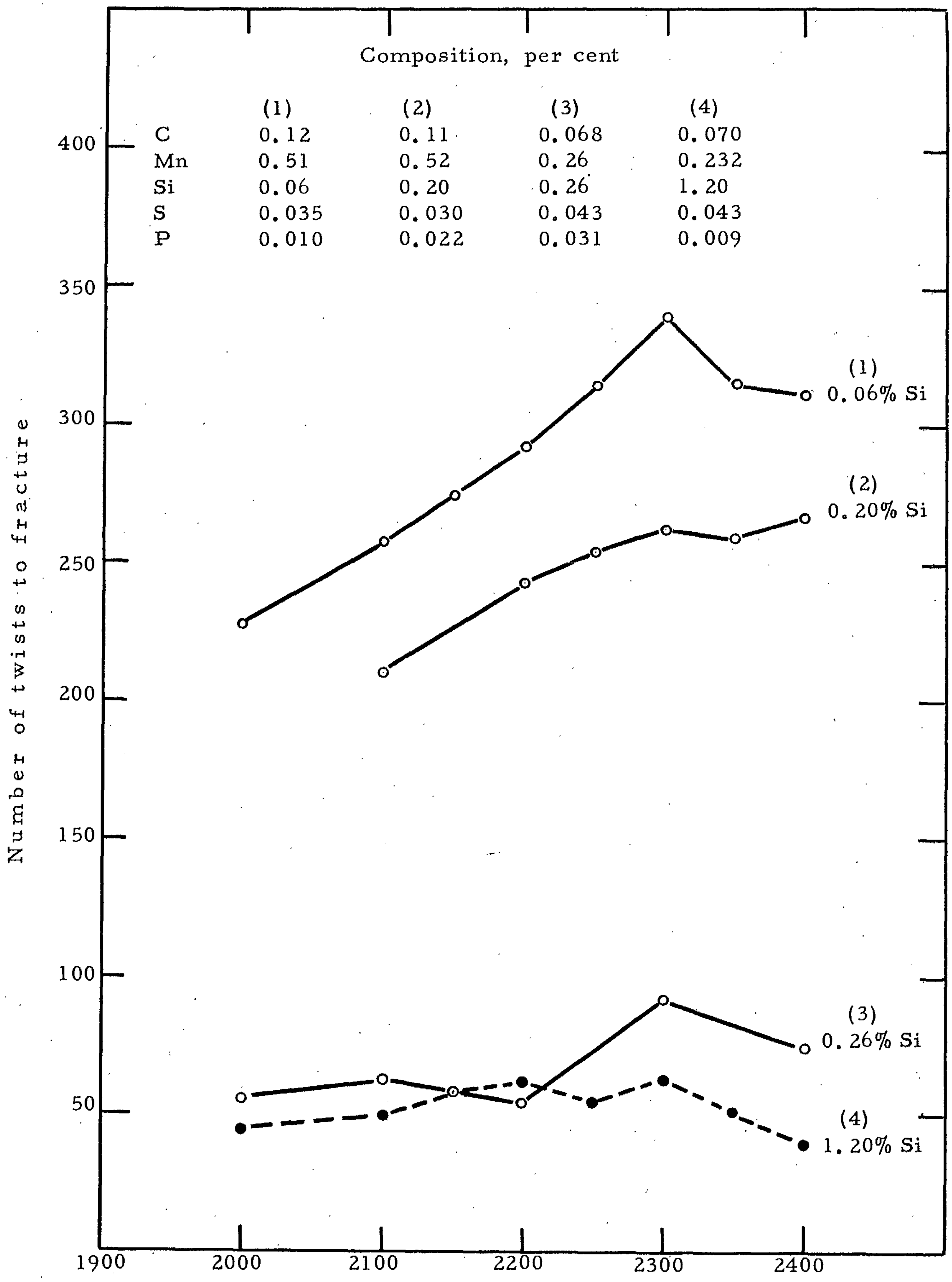


Fig. 25. - Effect of silicon on hot-workability of low-carbon steels.
(After: H. K. Ihrig, ref. 4)

Composition, per cent

	(1)	(2)	(3)	(4)	(5)	(6)
C	0.06	0.16	0.16	0.11	0.052	Monel
Mn	0.26	0.57	0.51	0.47	0.49	
Si	0.05	0.24	0.18	0.01	0.13	
Ni	99.43	3.55	5.05	30.06	43.50	67%Ni:30%Cu
S	0.005	0.013	0.019	0.042	0.008	(1%Mn 1%Fe)
P		0.013	0.019	0.010	0.011	

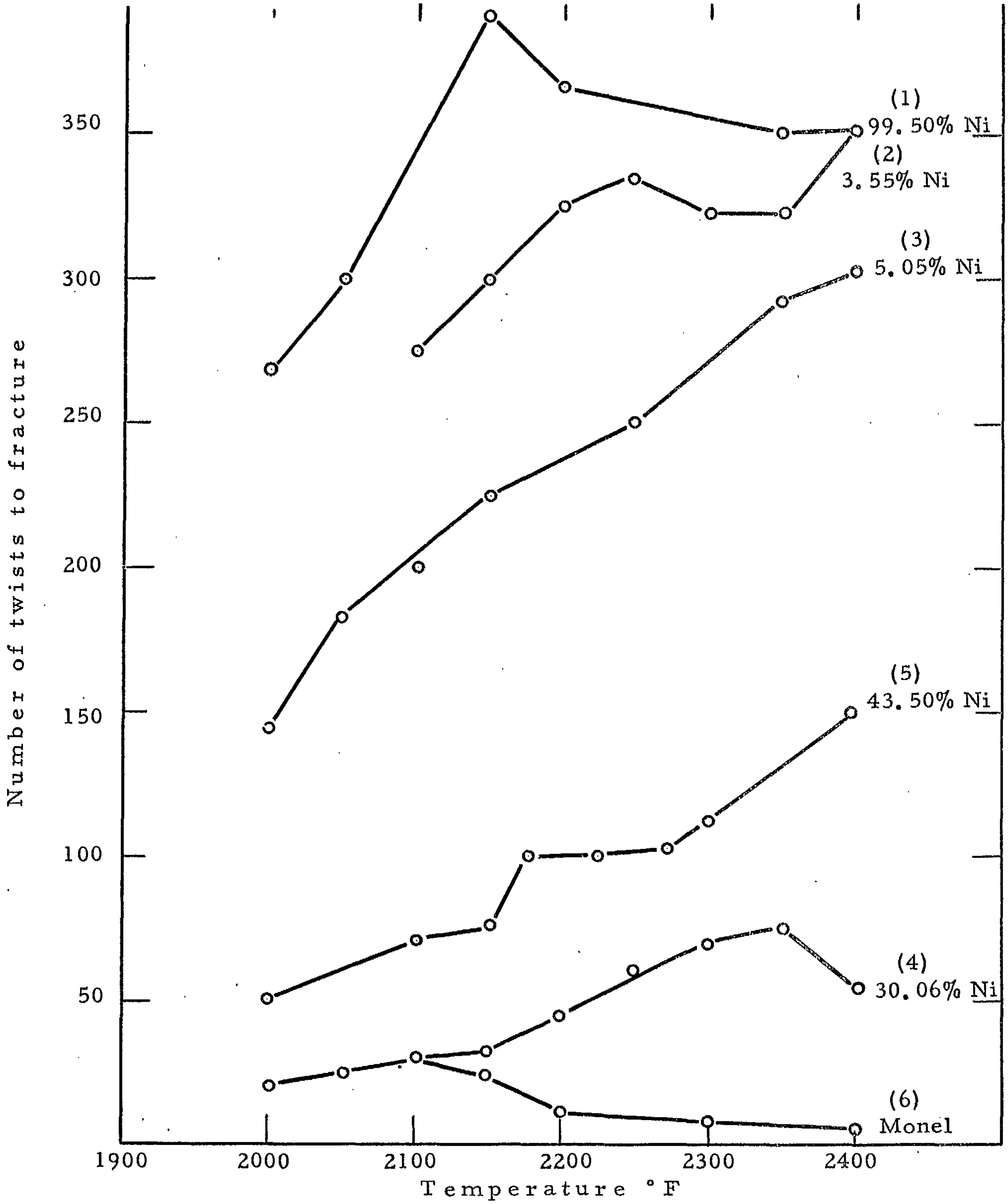


Fig. 26. - Effect of nickel on hot-twist characteristics of low-carbon steels. (After: H. K. Ihrig, ref. 4)

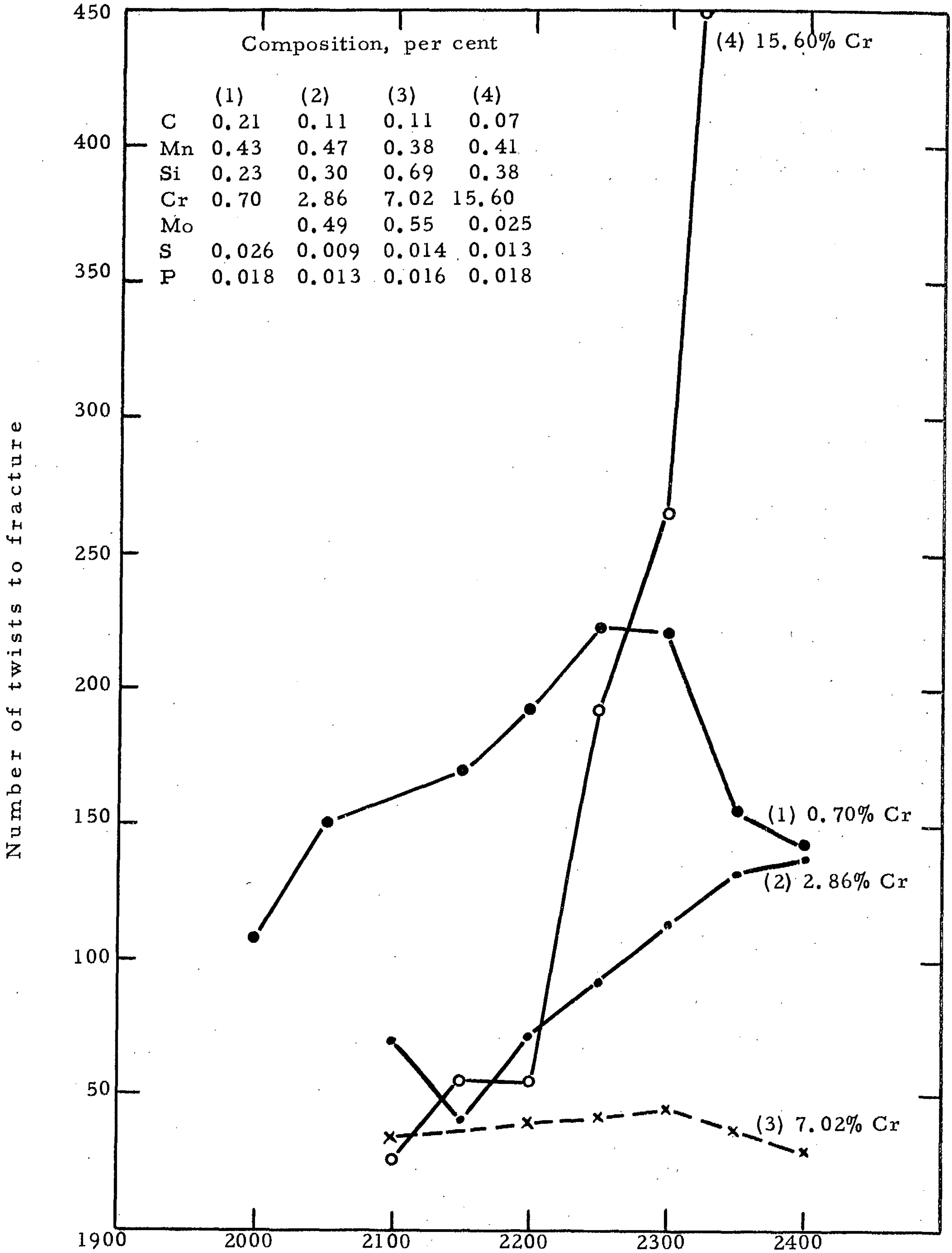


Fig. 27. - Effect of chromium on hot-workability of carbon steels. (After: H. K. Ihrig, ref. 4)

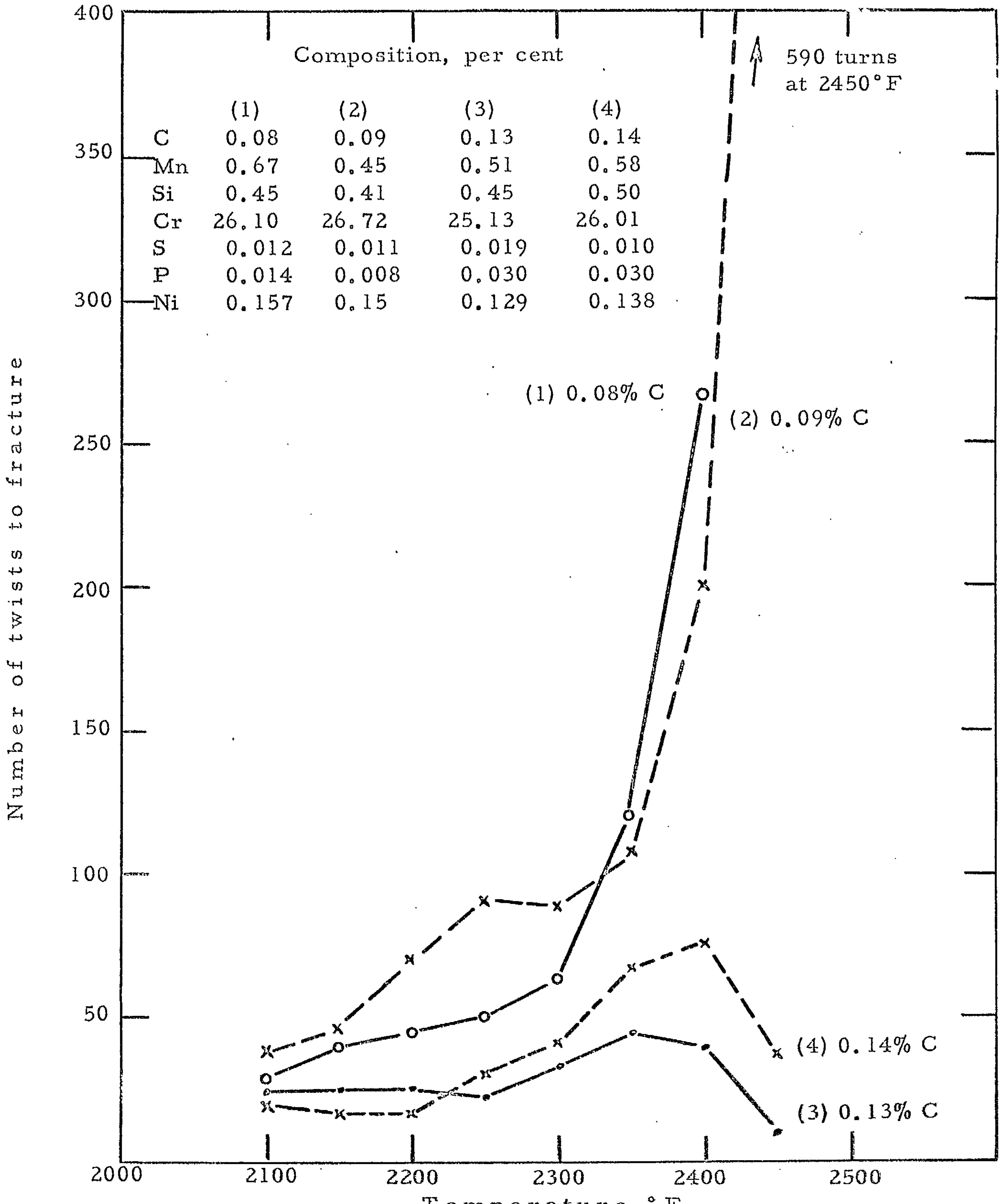


Fig. 28. - Effect of carbon on hot-workability of straight chromium steels of the type 446.

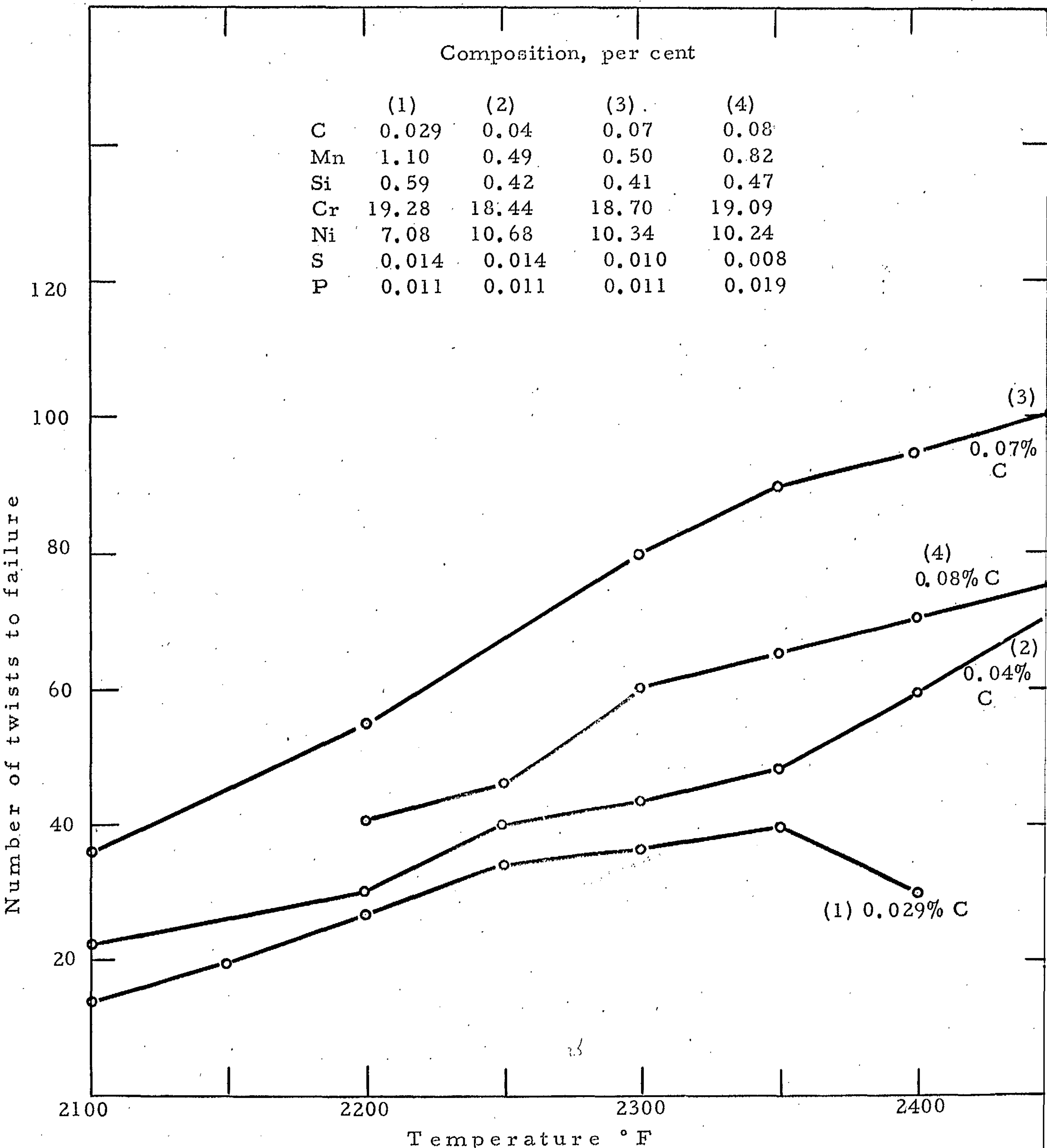


Fig. 29. - Effect of carbon on hot-workability of stainless steel of the type 304. (After: H. K. Ihrig, ref. 4)

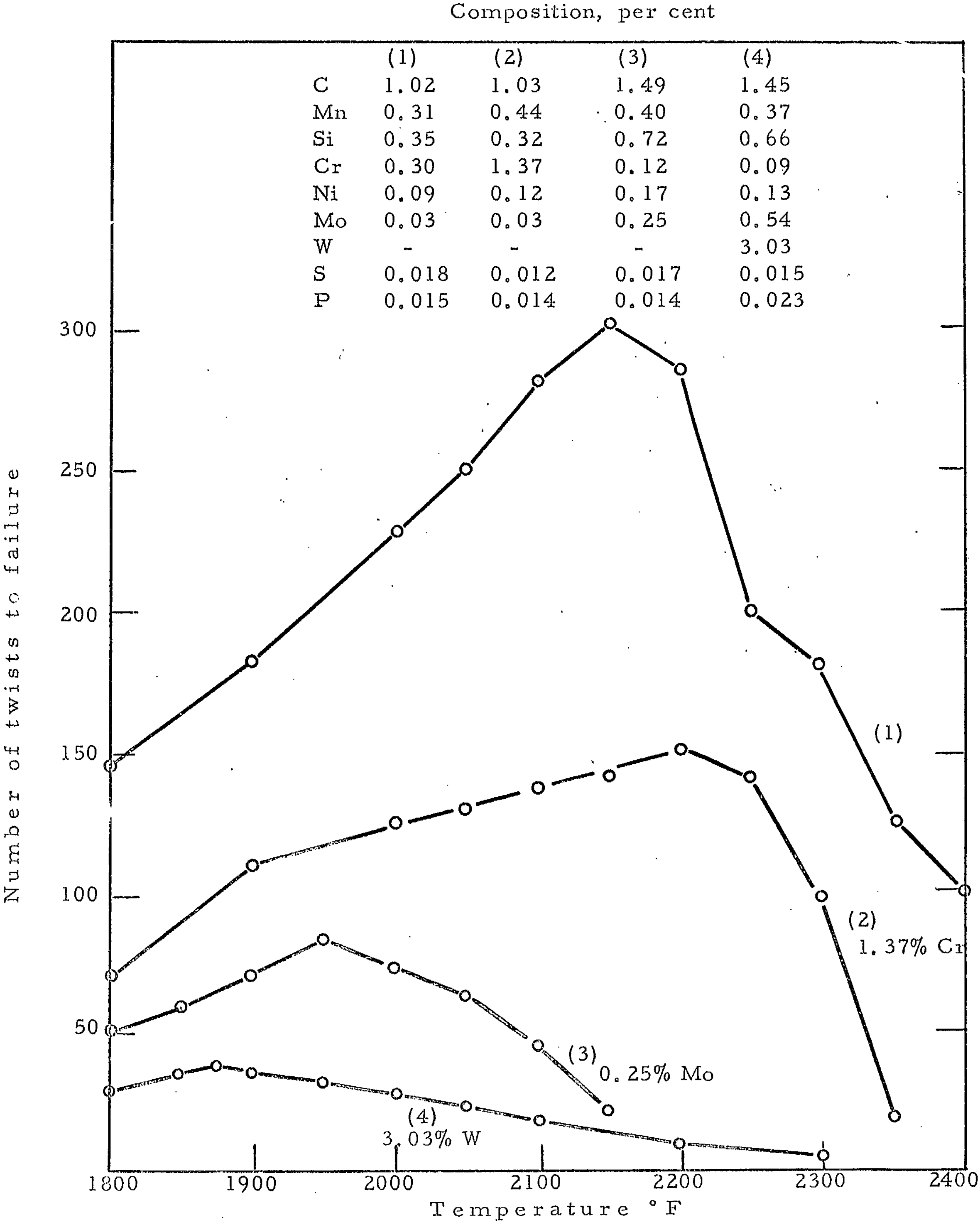


Fig. 30. - Effect of alloying elements on hot-workability of steels containing over 1% of carbon.
(After: C. L. Clark, ref. 5)

Composition, per cent

	(1)	(2)	(3)	(4)	(5)
C	0.13	0.14	0.12	0.074	0.022
Mn	0.47	0.42	0.48	1.37	1.60
Si	0.03	0.31	0.23	0.50	0.32
Cr				18.59	18.08
Ni				10.44	11.40
Mo		0.46	0.53		2.35
S	0.028	0.020	0.025	0.013	0.0107
P	0.013	0.016	0.016	0.017	0.015

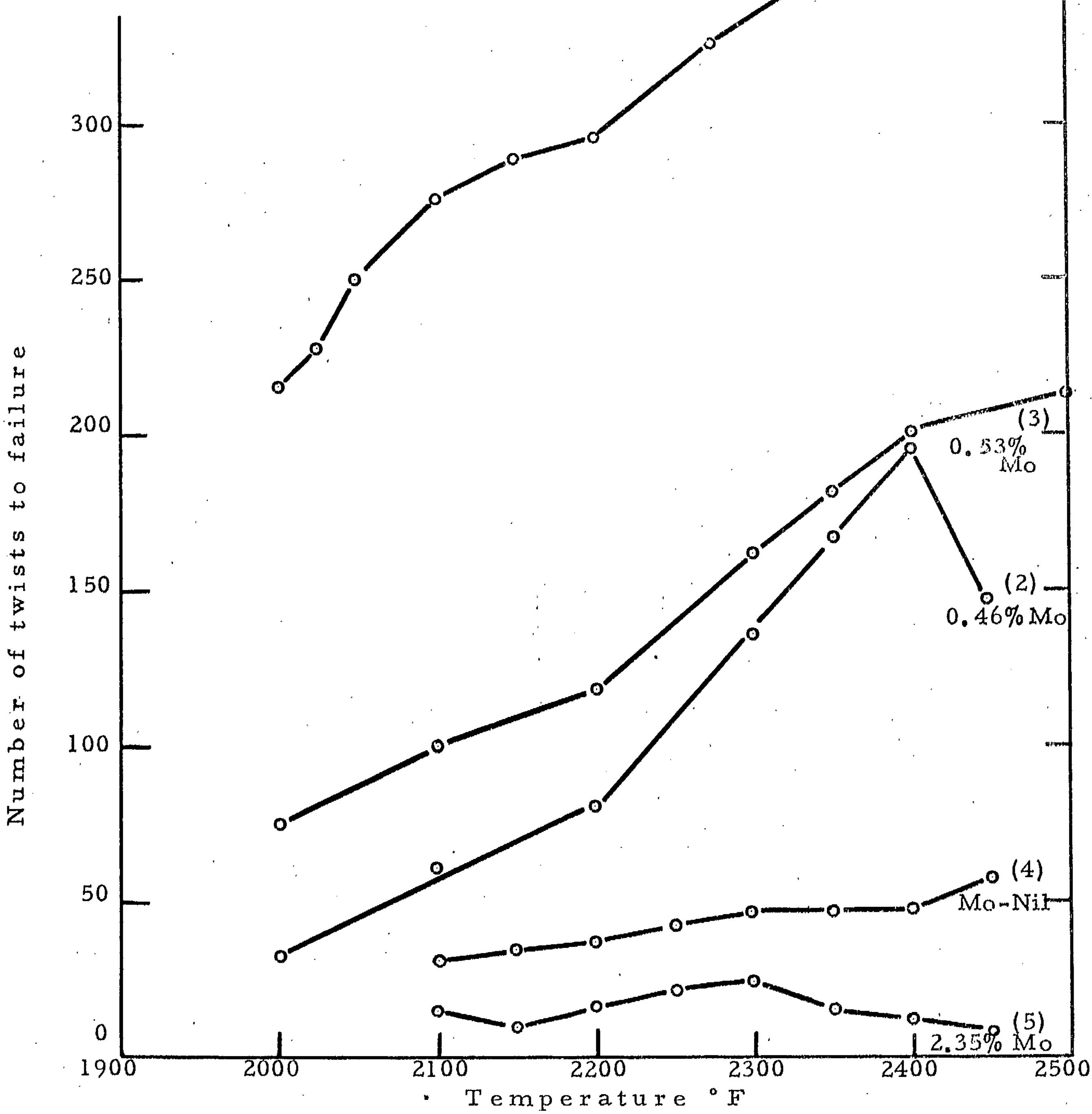


Fig. 31. - Effect of molybdenum on hot-workability of low-carbon and nickel-chromium steels.
(After: H. K. Ihrig, ref. 4)

Composition, per cent

	(1) 18:8	(2) 18:12+Cb	(3) 18:12+Ti	(4) 18:8+S	(5) 25:12	(6) 25:20
C	0.05	0.07	0.06	0.12	0.06	0.11
Mn	0.52	1.75	1.33	0.94	1.55	0.58
Si	0.52	0.68	0.28	0.35	0.42	0.75
Cr	17.78	18.85	17.41	18.08	24.96	23.60
Ni	9.60	12.87	10.03	8.85	13.40	20.65
Mo			0.06	0.24	0.01	0.03
Cb		0.82				
Ti			0.43			
S	0.012	0.017	0.013	0.239	0.017	0.017
P	0.006	0.012	0.021	0.022	0.011	0.013

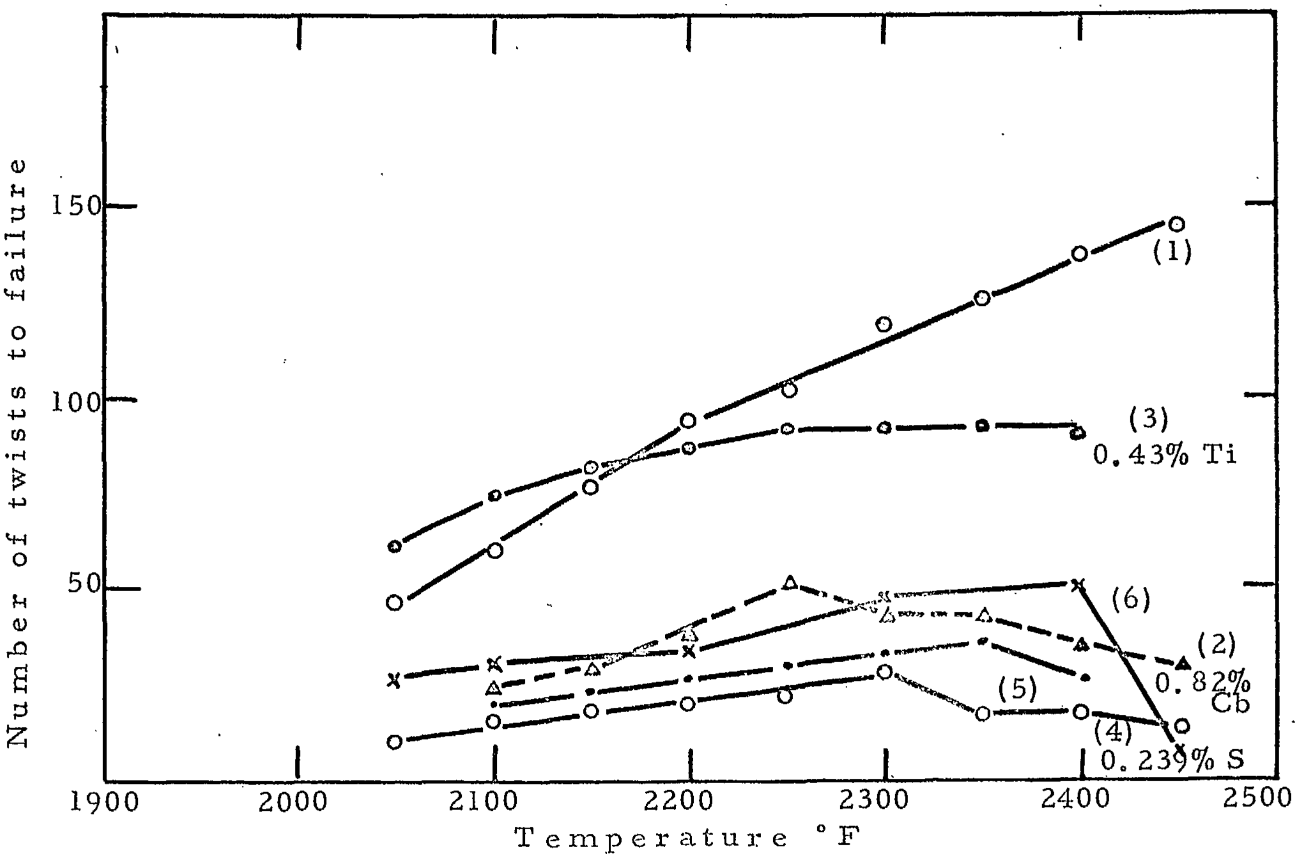


Fig. 32. - Hot-workability curves of various grades of austenitic stainless steels.
(After: C. L. Clark and J. Russ, ref. 6)

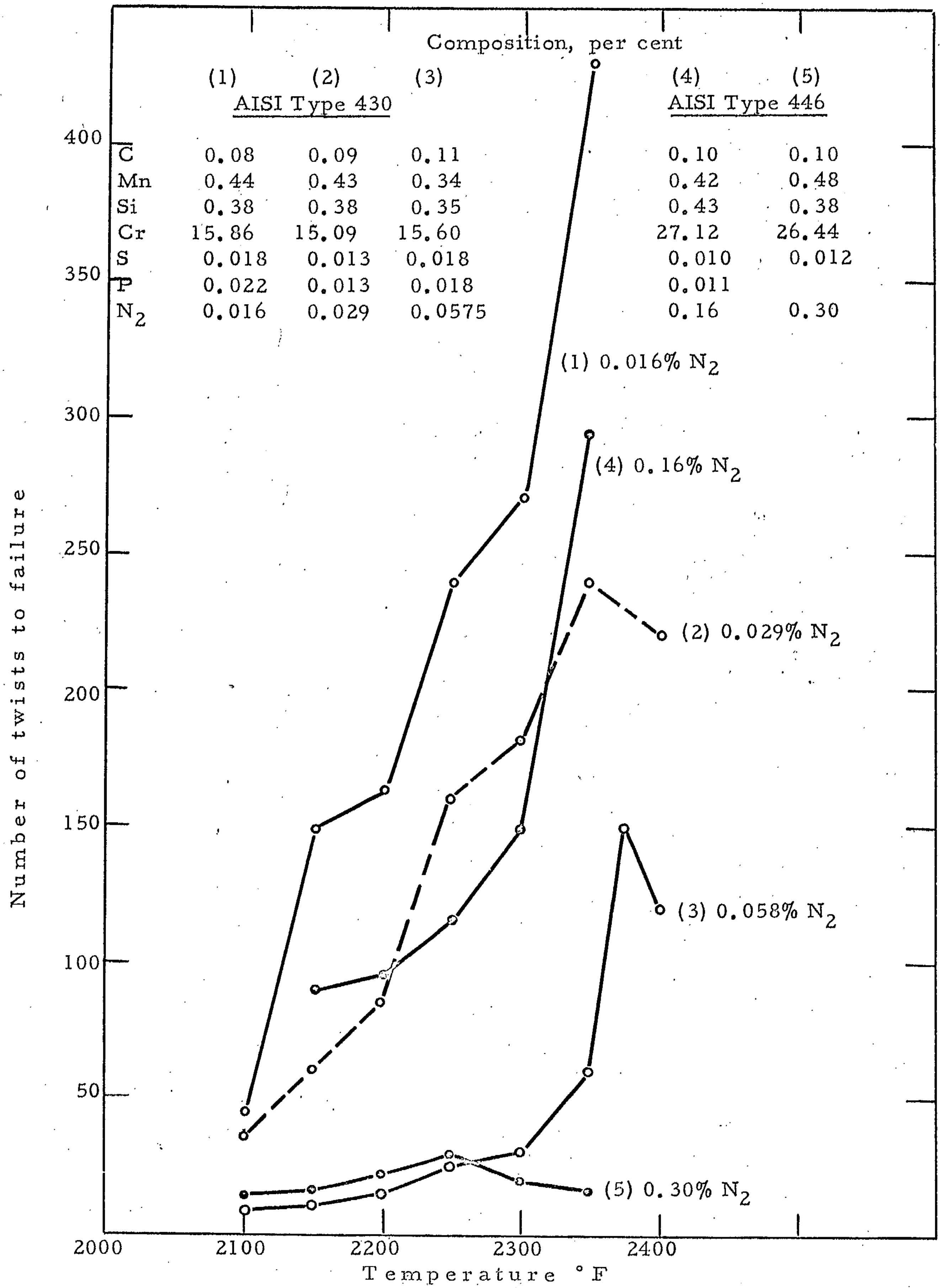


Fig. 33. - Effect of nitrogen on hot-workability of straight chromium steels of the types 430 and 446.
(After: H. K. Ihrig, ref. 4)

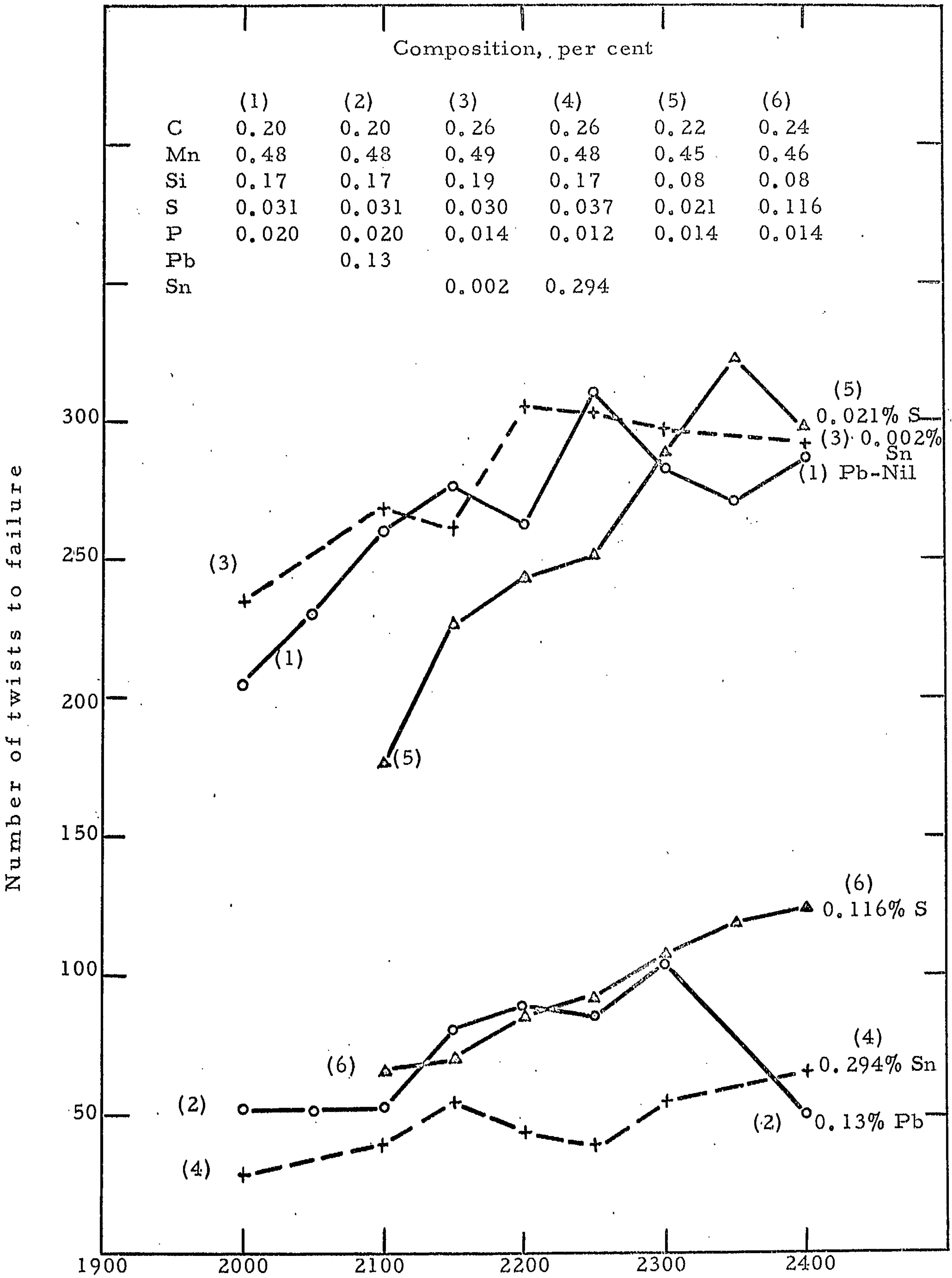


Fig. 34. - Effect of tin and lead on hot-workability of 0.20-0.25% carbon steel.
(After: H. K. Ihrig, ref. 4)

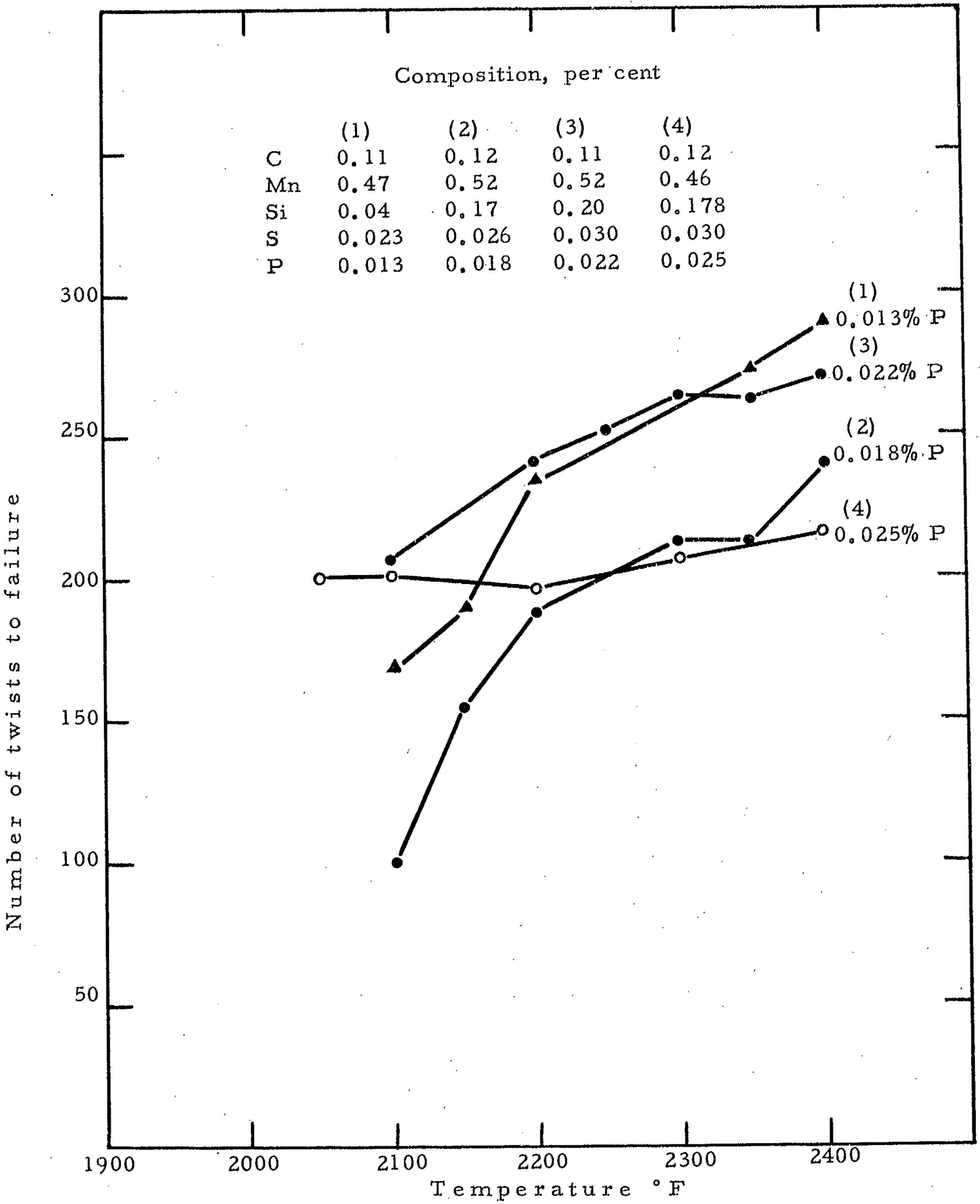


Fig. 35. - Effect of phosphorus on hot-workability of low-carbon steel.
(After: H. K. Ihrig, ref. 4)