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SPLIT FRACTURES IN TENSION TESTS OF STEEL

H. H. BLEAKNEY

PHYSICAL METALLURGY DIVISION

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SPLIT FRACTURES IN TENSION TESTS OF STEEL

by

H. H. Bleakney*

ABSTRACT

This report describes an investigation of the mechanism by which split fractures are produced in tension tests of steel. As part of the attempt to determine the conditions under which such fractures occur, a 4½ x 4½ inch billet of steel containing 0.23% carbon, 3.20% chromium and 0.55% molybdenum was obtained, and sixteen 1-inch-square test bars were cut from it. These were quenched variously in water, oil, and air, from 1600°F (870°C) and tempered at 1300°F (705°C). Almost the whole range of fractures, including cup-and-cone, star, and splits of varying severity, were obtained from subsequent tension tests. Excellent properties were obtained in all cases, so that variations were too slight to show any correlation with fracture types. It was evident, in these tests, that a rather delicate balance existed in the stress systems involved, and it appeared that variations in the type of fracture found must be attributable to variations in the distribution of segregates and non-metallics.

Transverse tests from a forged slab of the billet all yielded cup-and-cone fractures, attributable to the lowering of transverse cohesion by the adverse distribution of the segregates and non-metallics. Annealed longitudinal samples of the slab also gave cup-and-cone fractures; these were attributed to the weakening effect of the pearlitic structure produced by annealing.

The conclusion was drawn that cup-and-cone fractures occurred when the axial breaking stress reached the axial breaking strength before the transverse breaking stress reached the transverse breaking strength and that split fractures occurred when the reverse effect occurred.

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Direction des mines

Rapport de recherches R 137

RUPTURES LONGITUDINALES LORS D'ESSAIS DE TRACTION DE L'ACIER

par

H. H. Bleakney*

RÉSUMÉ

Le présent rapport est un exposé des recherches faites sur le processus de production des ruptures longitudinales lors d'essais de traction de l'acier. Ces ruptures sont toujours accompagnées de ruptures transversales à l'échantillon. Pour essayer de determiner le régime de production de telles ruptures, on a pris une billette d'acier de 4 1/2 pouces sur 4 1/2, à 0.23 p. 100 de carbone, 3.2 p. 100 de chrome et 0.55 p. 100 de molybdène. On y a découpé 16 éprouvettes d'un pouce carré. Chaque éprouvette fut trempée à partir de 1600°F (870°C) dans l'eau, dans l'huile ou dans l'air avant de lui donner un traitement de revenu à 1300°F (705°C). Des essais de traction subséquents ont permis d'obtenir toute la série de cassures, y compris celles en forme de cône ("cup and cone") et en forme d'étoile ainsi que celles obtenues à différents dégrés dans la direction longitudinale. Dans tous les essais, l'acier avait d'excellentes caractéristiques, si bien que les variations étaient trop faibles pour révéler la moindre corrélation avec les genres de cassures. Ces essais ont fait ressortir que l'ensemble des efforts étaient assez précairement équilibrés. Il semble que les variations du genre de cassures obtenues doivent être attribuées à la répartition des produits de ségrégation et des corps non-métalliques.

Des échantillons furent pris dans une brame forgée à partir de la billette. Les essais de traction dans la direction transversale à la déformation mécanique ont donné des cassures en forme de cône; celles-ci sont attribuables à la diminution de cohésion dans la direction transversale à cause de la répartition défavorable des produits de ségrégation et des corps non-métalliques. À la suite d'un traitement de recuit, des échantillons de la brame, pris cette fois dans la direction longitudinale, ont donné le même genre de cassures; on explique l'origine de ces dernières par l'effet affaiblissant de la structure perlitique obtenue au recuit.

L'auteur en a conclu que les cassures en forme de cône se produisent quand les tensions de rupture dans la direction longitudinale atteignent le point de rupture dans cette même direction avant que les efforts de rupture dans la direction transversale atteignent le point de rupture dans cette dernière direction. Ainsi il explique que les ruptures longitudinales ont lieu quand l'effet inverse se produit.

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INTRODUCTION

During the first quarter of this century, most of the tensile fractures of steel test specimens displayed the now familiar "cup and cone" appearance. However, with the development of the automobile industry and the associated use of quenched and tempered alloy steels, a different kind of fracture began to appear with increasing frequency. Figure 1 illustrates a typical example. In this picture the cup-and-cone features remain but they are modified by radial markings that impart a starry appearance to the fractured surface. This kind of fracture became known, therefore, as a "star" fracture.

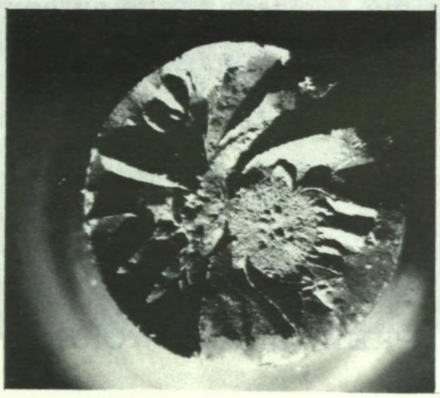


Figure 1 - SAE 3140 steel, quenched in oil and drawn at 1250°F.

As higher alloy steels came into use, occasional fractures such as that shown in Figure 2 were found. The shattered appearance of these breaks was rather disquieting to those responsible for the use of the steel, since it conveyed an impression of brittleness. However, it was soon observed that in these cases the test specimens had good ductility; indeed, at comparable strength levels they displayed reductions in area that compared most favourably with samples of steels that showed more conventional fractures. These steels, therefore, have continued to be used with confidence and have proved eminently satisfactory.

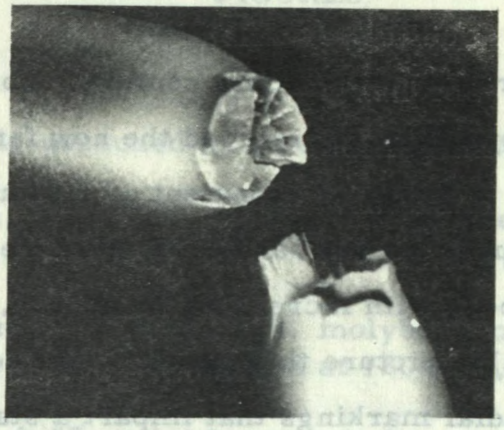


Figure 2 - 16% chromium, 2% nickel, 0.12% carbon steel, quenched in air from 1575°F and drawn at 1200°F.

At the same time, however, the author believes that many metallurgists must share his wish to learn more about the mechanism by which the splits are produced. This report describes an attempt to provide a beginning in the search for such an explanation.

PRELIMINARY WORK

For obvious reasons, this investigation of the conditions required to produce split fractures began with the attempt to reproduce them. Because the splits were known to be associated with deep-hardening steel, one of the more highly alloyed automotive types was examined first. (Type 410 steel was known to produce these fractures but a less highly alloyed steel was desired, to minimize the possible complicating effect of segregation.) The first tests, therefore, were made on a steel of the following nominal composition: (%)

Carbon	Manganese	Chromium	Nickel	Molybdenum
0.45	0.75	0.75	1.75	0.40

Four 1-inch round and four 3/4-inch round samples of this steel were austenitized at 1550°F (845°C), after which one of each size was quenched in water, one of each quenched in oil, one of each air-cooled, and the remaining two furnace-cooled. All were then tempered at 1200°F (645°C). In subsequent tension tests the furnace-cooled samples showed simple cup-and-cone fractures, the air-cooled samples had fractures similar to Figure 1, and both the oil-quenched and water-quenched samples, illustrated in Figure 3, yielded fractures with a more sharply defined "star" appearance than Figure 1. The mechanical properties revealed in these tests are shown in Table 1.

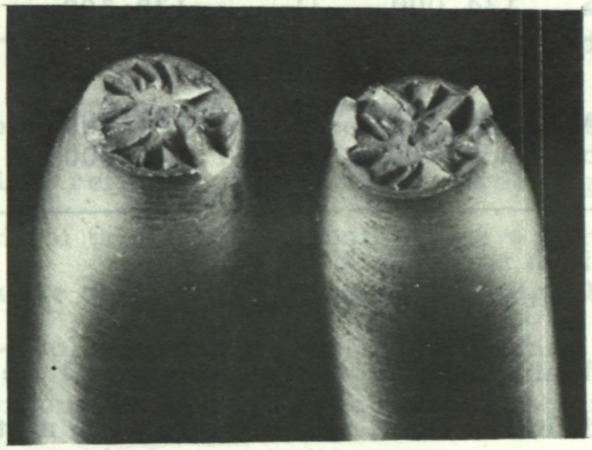


Figure 3 0.4% carbon, nickel, chromium, molybdenum steel, quenched from 1550°F and drawn at 1200°F.

TABLE 1

Properties of Nickel, Chromium, Molybdenum Steel

Cooling Medium		Ultimate Strength, psi	0.2% Proof Stress, psi	Reduction in Area, %
Furnace	a	108,000	78,000	58.6
	b	110,500	79,000	53.2
Air	a	112,000	86,000	62.4
	b	122,000	102,500	61.2
Oil	a	134,000	120,300	63.6
	b	137,000	128,500	58.6
Water	a	136,500	124,700	61.4
	b	136,000	126,000	58.4

a - Treated in 1-inch round section.
b - Treated in 3/4-inch round section.

Failure to obtain split fractures from any of these samples made it necessary to try a different steel. A small billet of a steel containing 0.25% carbon, 0.9% manganese, 1.0% silicon, 1.5% chromium, 1.0% molybdenum and 0.45% vanadium was available and, principally for that reason, was investigated. The billet was forged to a bar about $1\frac{1}{2}$-inch round, machined to 1-inch round, and cut into four test-piece lengths. These were austenitized for $\frac{1}{2}$ hour at 1900°F (1040°C) and cooled as follows:

First bar - water quenched.
Second bar - cooled in air to 1400°F (760°C) approx., then water quenched.
Third bar - cooled in air.
Fourth bar - cooled in the furnace.

All samples were tempered at 1350°F (720°C) and subsequent tension tests showed the properties presented in Table 2.

TABLE 2

Properties of Chromium, Molybdenum, Vanadium Steel

Cooling Medium	Ultimate Strength, psi	0.2% Proof Stress, psi	Reduction in Area, %
Furnace	163,000	114,000	25.2
Air	161,500	126,500	43.4
Air to 1400°F then water	144,000	126,000	61.8
Water	147,000	131,700	63.7

These somewhat anomalous results, with respect to both strength and ductility, possibly reflect a precipitation hardening effect that is a known characteristic of this steel. In both of the water-quenched samples, pronounced splits were observed, very similar to those illustrated in Figure 2. The air-cooled sample had the main features of a cup-and-cone fracture, but the bottom of the cup and the corresponding section of the cone were very flat, and had a crystalline appearance, and extended over almost the full cross-section of the fractured ends. In the furnace-cooled sample this condition was present to an extreme degree. The flat crystalline break, at right angles to the axis of the specimen, extended virtually across the full section, with only vestiges of a rim visible on one broken end and a suggestion of a bevel around the perimeter of the other. Because of this unusual response to heat treatment, it was considered necessary to try to find a steel that would yield split fractures while responding more conventionally to heat treatment.

TESTS OF 3% CHROMIUM, 0.5% MOLYBDENUM STEEL

Selection of a steel for further investigation was influenced by consideration of the evidence that a deep hardening steel with high potential ductility was necessary for development of split fractures. The availability of a steel containing about 3% chromium, 0.5% molybdenum and 0.25% carbon seemed to offer not only convenience of procurement but promise of success.

Procurement of this material was also influenced by the desirability of investigating transverse as well as longitudinal properties. The supplier produces 4½-inch, round-cornered square billets from 18-inch ingots as standard procedure, and as this size lent itself to the requirements of the investigation, a one-foot length of such a billet was obtained.

The reported analysis was as follows:

carbon 0.23%, manganese 0.56%, phosphorus 0.027%, sulphur 0.017%, silicon 0.25%, chromium 3.20%, and molybdenum 0.55%.

The billet was cut into two parts, from one of which sixteen test samples were obtained, each a little over one inch square by 5½ inches long. The remainder of the billet was forged and rolled to a flat section about 5½ inches wide by a little over one inch thick. The sixteen samples were used in the attempt to reproduce split fractures, and also to obtain information about the uniformity of properties from outside to inside of the billet. The flat was designed to provide tests for a study of transverse versus longitudinal properties.

Billet Tests

For exploratory purposes, three of the four corner test samples from the billet were machined to 1-inch round, 7/8-inch round and 3/4-inch round respectively, austenitized for ½ hour at 1600°F (870°C), quenched in water, and tempered at 1325°F (720°C).

The fractures obtained in subsequent tension tests had not split. Two of them resembled that illustrated in Figure 1 and the third displayed a well-developed cup and cone. This specimen was from the one-inch round sample. The physical properties obtained are shown in Table 3.

TABLE 3

Properties of 3% Chromium, 0.5% Molybdenum Steel

Treated Diameter, inches	Ultimate Strength, psi	0.2% Proof Stress, psi	Reduction in Area, %
1	108,000	82,800	73.9
7/8	104,000	82,500	74.3
3/4	105,000	84,400	74.3

The fractures obtained in these preliminary tests did not encourage the hope of finding split fractures in this steel, but testing was continued in order to extract what information was available from the remaining test bars and also because of the chance that some split fractures might be found. Two more exploratory test bars were heat treated, therefore, one from the surface group and one from the interior, to look for indications of possible variation in properties from outside to centre. The two bars were quenched in water after being held at 1600°F (870°C) for 30 minutes, then tempered at 1300°F (705°C). The lower draw temperature was chosen merely to see whether it would make any difference to the results, and the subsequent tension tests revealed the properties shown in Table 4.

TABLE 4

Surface and Interior Properties

Location	Ultimate Strength, psi	0.2% Proof Stress, psi	Reduction in Area, %
Outside	102,500	83,600	74.9
Interior	103,000	84,200	74.3

The differences shown are clearly insignificant; but a very significant result was the appearance of split fractures, illustrated in Figure 4. Although Figure 4 shows much less shattering than the example seen in Figure 1, it displays clearly the definitive characteristics of split fractures.

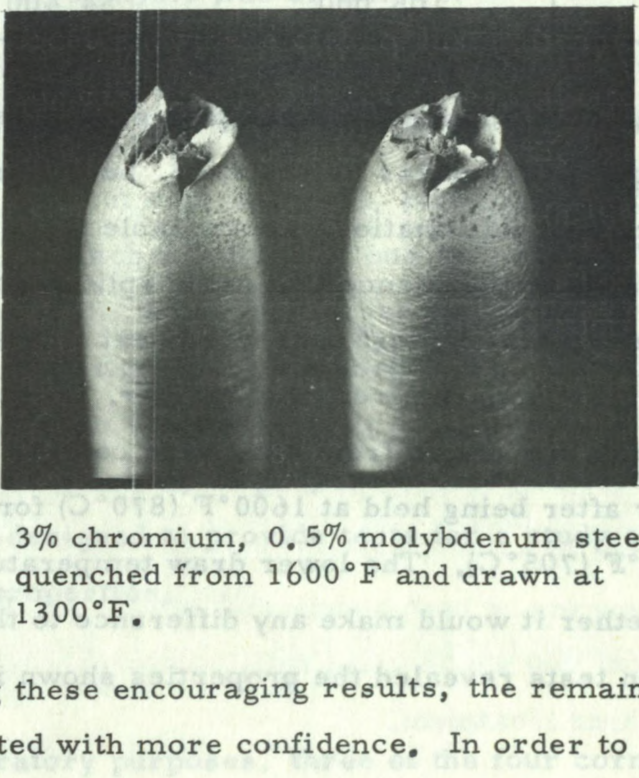


Figure 4 - 3% chromium, 0.5% molybdenum steel, quenched from 1600°F and drawn at 1300°F.

Following these encouraging results, the remaining eleven test bars were heat treated with more confidence. In order to obtain as much information as possible, some of the bars were cooled in air from the austenitizing temperature, some were quenched in oil, and two were quenched in iced brine. The results of the subsequent tension tests are given in Table 5, together with those of the previous water-quenched tests of Table 4.

In this table the types of fractures obtained are classified in the column headed "Fractures".

TABLE 5

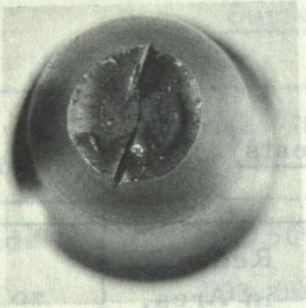
Collected Results of Billet Tests*

Quenching Medium	Location	Ultimate Strength, psi	0.2% Proof Stress, psi	Reduction in Area, %	Fracture
Oil	Outside	100,900	81,000	73.5	Mild split
	"	100,900	81,000	73.9	Single split
	Interior	101,600	81,400	74.1	Single split
Air	Outside	101,600	81,400	72.9	Medium split
	"	101,500	81,200	72.9	" "
	"	101,300	81,500	71.2	Pronounced split
	"	101,000	81,000	72.3	Mild split
	Interior	101,500	80,000	72.7	" "
	"	100,300	80,400	71.6	Pronounced star
Brine	Outside	99,400	80,400	73.5	Mild split
	"	101,500	81,100	75.1	Medium split
Water	Outside	102,500	83,600	74.9	Medium split
	Interior	103,000	84,200	74.3	Mild split

*Above tests all on 1-inch square samples drawn at 1300°F.

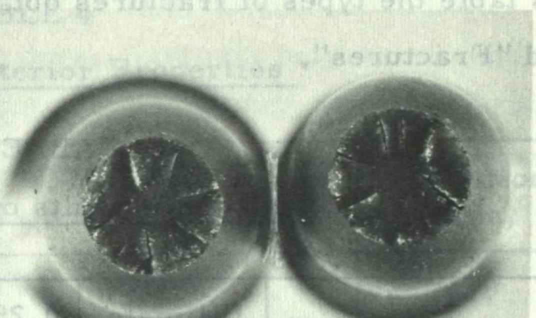
Figure 5 illustrates a fracture described as "single split", and Figure 6 shows the appearance of one described as "pronounced star".

A "mild split" is shown in Figure 4 and a pronounced split in Figure 2. The significance of the results presented in Table 5 will be discussed later, but attention is drawn to the high degree of uniformity shown, from outside to interior, in the properties obtained by any given treatment.



X2.5

Figure 5 - Same steel and treatment as Figure 4.



X2.5

Figure 6 - Same steel and treatment as Figure 4.

Forged and Rolled Flat

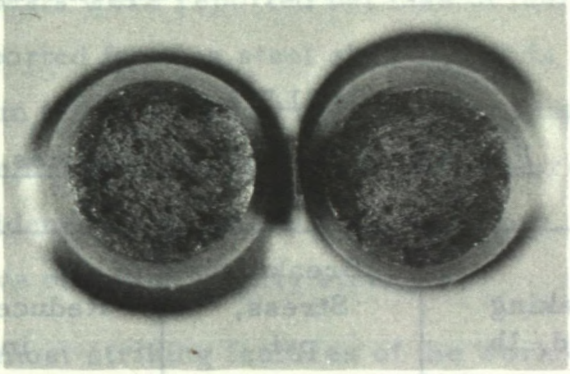
As stated earlier, half of the original billet was forged and rolled to a flat section about one inch thick and $5\frac{1}{2}$ inches wide. The final length was about 20 inches, and, from this, four one-inch-square bars were cut at right angles to the direction of rolling. Four other similar bars were cut parallel to the rolling direction. These bars were all heated to 1600°F (870°C), held for one-half hour, quenched in water, and then tempered for two hours at 1300°F (705°C). The properties subsequently found in tension tests are reported in Table 6.

TABLE 6

Transverse and Longitudinal Properties

Direction	Ultimate Strength, psi	0.2% Proof Stress, psi	Reduction in Area, %
Longitudinal	102,000	83,500	74.3
	105,200	83,400	73.8
	105,500	84,900	75.2
	104,500	83,200	75.2
Transverse	106,500	84,000	54.1
	106,000	84,600	54.2
	105,500	84,900	54.6
	105,000	84,700	53.6

The appearance of the fractures obtained from the longitudinal specimens is shown in Figure 5. It is essentially a cup-and-cone fracture, with a single split on one diameter. The fractures of the transverse test specimens are illustrated in Figure 7; the influence of the directional fibre is readily apparent.



X2.5

Figure 7 - Transverse test taken from forged end of billet of 3% chromium, 0.5% molybdenum steel, quenched and drawn.

In order to investigate the extent to which the lower ductility of the transverse results represents cohesive weakness, further tests were conducted and the breaking loads carefully noted. The results are presented in Table 7.

TABLE 7

Comparison of Breaking Strengths of Transverse and Longitudinal Tension Tests

Direction	Ultimate Strength, psi	Breaking Load, lb	Breaking Stress, psi	Reduced Area, sq. in.
Longitudinal	100,300 99,600	10,700 10,800	214,000 212,000	0.050 0.051
Transverse	110,400	15,300	166,000	0.092

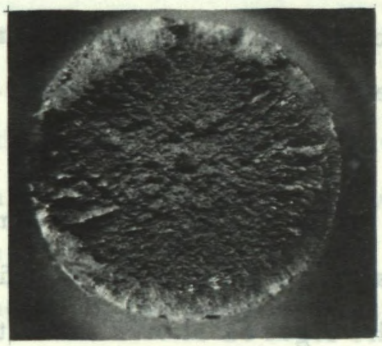
Finally, a group of three test bars, cut longitudinally from the forged slab, were annealed by heating to 1600°F (870°C), holding for 30 minutes, and then transferring them to a furnace held at 1300°F (705°C); after being held at that temperature for two hours the samples were cooled to room temperature in air. Subsequent tension tests gave the results shown in Table 8.

TABLE 8

Properties of Annealed Samples

Ultimate Strength, psi	Breaking Load, lb	Breaking Stress, psi	Reduced Area, in.	Reduction in Area, %
95,000	13,700	159,500	0.086	56.6
94,800	14,000	160,000	0.088	55.5
94,200	13,900	161,800	0.086	56.6

The appearance of the fractures seen in these tests is shown in Figure 8.



X4

Figure 8 - Same steel as Figure 7, but longitudinal section annealed to produce pearlitic structure.

DISCUSSION

Discussion of the results obtained in this investigation will be largely confined to those obtained from the 3% chromium, 0.5% molybdenum steel. The previous tests were reported because of their introductory value. All the properties reported for this steel show that it is deep hardening, that it is very uniform from the outside to the centre, and that the properties of tests taken transverse to the rolling direction must be regarded as highly satisfactory. The evidence obtained from it, therefore, may be confidently taken as representative of a high quality steel.

One of the most striking features of the work on this steel, which began so unpromisingly, is the fact that among the sixteen tests taken from the unforged billet the whole range of fractures from cup and cone to pronounced splits is included. The next striking fact is the futility of attempting to correlate the types of fracture obtained with the corresponding properties shown in Table 5. Study of these fractures suggests that there are two competing influences at work, and that the range of fractures indicated in Table 5 argues that they are rather evenly balanced. One of these influences must be the normal stress parallel to the specimen axis; when this influence is dominant fracture begins as a minute fissure on the axis that spreads rapidly along all radii until, at a certain distance from the centre, the spread direction changes so that by the time the fissure reaches the surface a conical ridge is left on one end of the broken test piece and a conical bevel on the other.

Where stars or splits occur, the evidence points to radial and tangential stresses, intensified by advanced necking, as the splitting force. Actually, examination of the figures shows that star fractures are the result of incipient splits and that the radial markings are caused by small fissures. When such fissures are sufficiently pronounced to reach the surface of the specimens, they qualify for the more imposing title of "splits". Since no evidence was found in Table 5 to explain why one type of fracture occurred rather than another, an answer was sought in an examination of transverse properties. Table 6 shows that the reduction of area in the transverse samples, although very good, is only a little over 70% of that found in the longitudinal tests. This result, of course, represents the effect of directional deformation on the segregates and non-metallics in the steel. To investigate this effect further, the tests reported in Table 7 were made and the results show that the breaking stress transverse to the direction of rolling is about 3/4 of that parallel to the rolling direction. From the evidence thus far presented, it is a reasonable hypothesis that the kind of fracture produced, in longitudinal tests, depends to a large extent on whether or not the axial stress attains the longitudinal breaking strength before the radial and tangential stresses reach the transverse breaking stress. In this context, it is obvious that the influence of segregates and non-metallics was the most variable factor, and hence the most influential in tipping the balance one way or the other to produce the various breaks indicated in Table 5.

The probable influence of segregates and non-metallics is also suggested by the fact that all the longitudinal tests of the forged slab showed single splits. Undoubtedly the forging geometry resulted in anisotropic deformation of the segregates in planes normal to the slab surface, thus bringing about a difference in the breaking strengths between the direction normal to the slab surface and that parallel to the surface. The geometry suggests that the splits are in planes parallel to the surface. It must be emphasized, however, that the influence of segregates is only significant under conditions such as existed in the tests of Table 5, where there was a balance to be tipped. The results reported in Table 8 show that the structure of the steel is of primary importance. In the tests of Table 8 annealing produced a relatively brittle pearlitic structure and the consequent reduced reduction in area. In this condition the axial stress reaches the breaking stress (lowered by the pearlite) before necking has advanced sufficiently to develop the hoop stresses sufficiently to overcome the transverse breaking strength. It is understood, of course, that the cited breaking stresses are average stresses and that the cohesive strength is much higher. It has been assumed, however, that the breaking stresses give a measure of the cohesive strength at the point of incipient fracture.

CONCLUSION

The evidence indicates that whether the fracture of a steel tension test specimen will be cup-and-cone, star, or split, depends primarily on whether or not the axial stress applied reaches the longitudinal breaking strength before the stresses transverse to the axis of the specimen reach the transverse breaking strength. It is obvious that the answer to this question is to be found in the relative value of the two breaking strengths. Simple inspection of split fractures shows that they occur as a result of stresses, acting at right angles to the axis, that become intensified in the advanced stages of necking.

The evidence indicates that the structure of tempered martensite, obtained by quenching and drawing, produces the best values for reduction in area and thus promotes splitting. Annealing, on the other hand, produces a structure that disproportionately lowers the axial, as compared with the transverse, breaking strength and thus promotes the formation of cup-and-cone fractures. Split fractures, therefore, accompany high cohesive strength, the essential element in ductility(1), rather than brittleness.

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1. Bleakney, H. H., "Criteria of Ductility in Uniaxial Tension", Trans. Can. Inst. Min. Met., Vol. 65, p. 73 (1962).

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