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Tension Impact Tests With Circumferentially Notched Specimens

L. ENGLER and E. OROWAN

Technical Report No. 2
Office of Naval Research
Contract Number N5ori-07870

July 1954

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NOTCHED SPECIMENS

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L. ENGLER and E. OROWAN

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Massachusetts Institute of Technology
Department of Mechanical Engineering

D. I. C. 6949

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TENSION IMPACT TESTS WITH CIRCUMFERENTIALLY NOTCHED SPECIMENS

1. The problem.

It was found in a preceding investigation⁽¹⁾ that a cleavage crack produced at the temperature of liquid nitrogen at one edge of a ship steel plate never propagated as a cleavage crack when a tensile stress was applied to the plate at room temperature. Instead, extensive plastic deformation took place around the tip of the crack and this started to propagate as a ductile (shear or fibrous) crack until, after a very short run, it changed back to a cleavage crack which ran across the plate at high velocity. It was concluded from this observation that, contrary to the classical triaxial-tension theory of notch brittleness⁽²⁾⁽³⁾⁽⁴⁾, the essential factor in raising the tensile stress to the level of the brittle fracture stress was not plastic constraint giving rise to triaxial tension but the increase of the yield stress of steel with the rate of deformation. Under static loading, the velocity effect is initially absent in the plate specimen containing the crack; for this reason, plastic deformation, instead of cleavage fracture, takes place at the tip of the crack. In the course of this, a triaxiality of tension arises which may raise the maximum tensile stress up to 2 or 3 times the value of the uniaxial yield stress. If the tensile stress reaches the magnitude of the brittle strength, the ductile crack that has developed during the plastic deformation at the tip of the original cleavage crack changes back to the cleavage type. When the cleavage crack gathers

speed, the yield stress for any plastic deformation that may occur at its tip may be up to 2 or 3 times higher than at low rates of deformation⁽⁵⁾; consequently, the velocity effect may take over from the triaxiality effect the task of raising the tensile stress to the fracture level. If this occurs, the cleavage fracture becomes truly brittle, no longer requiring the relatively large plastic deformations needed for producing triaxiality.

This picture involves a considerable change in the interpretation of the transition temperature and of the significance of impact tests for engineering design in general. Fig. 1 illustrates the classical theory of the transition temperature. Curve Y is the uniaxial yield stress plotted as a function of the temperature; qY the highest tensile stress that can arise in a material of yield stress Y by notch constraint. The constraint factor q for an ideally sharp and deep notch is about 2.5 or 3, depending on the shape of the stress-strain curve. B is the brittle fracture stress (brittle strength); it is assumed not to decrease with increasing temperature as rapidly as the yield stress. The curves qY and B intersect at the transition temperature T_t ; below this temperature the tensile stress can be raised by a sufficiently effective crack or notch to the fracture level, above T_t it cannot. Of course, it has always been known that the yield stress depends on the velocity of straining: at high strain rates, the curves Y and qY rise and, since the strain rate cannot have an equally large effect on B, the transition temperature rises. This however, was regarded in the classical triaxial-tension theory as a secondary effect. The theory assumed that a minute amount of plastic

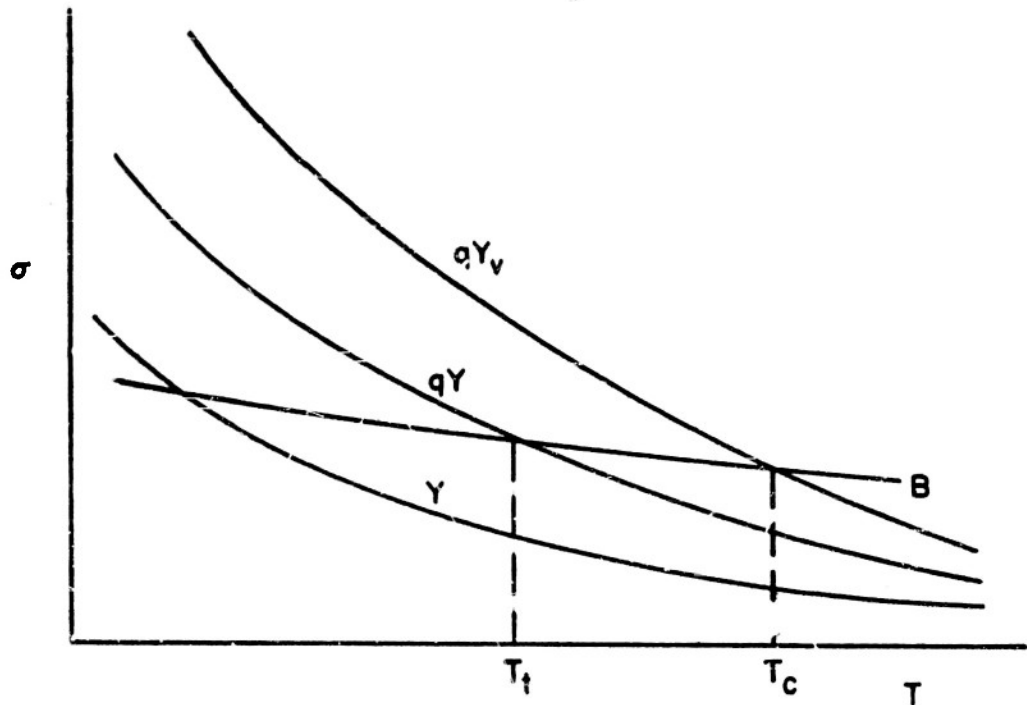


FIG. 1

deformation at the tip of the cleavage crack was sufficient to produce the necessary triaxiality of tension, so that the fracture could be almost brittle although plastic deformation was essentially involved. The experiments of Felbeck and Orcwan have shown that this is not so: for some reason that is not quite clear yet, the development of plastic constraint requires such extensive plastic deformation that the ensuing fracture, although mainly of the cleavage type, is far from being brittle (i.e., of low energy consumption). In genuinely brittle fracture, therefore, the increase of the yield stress with the velocity of deformation must be the primary factor in raising the tensile stress to the cleavage level.

If both plastic constraint and the velocity effect are capable of raising the tensile stress that can occur during yielding to the cleavage level, the combination of the two ought to be particularly effective. If either effect can double the stress, their combination should raise it by a factor 4. In Fig. 1, the curve qY_v represents the maximum to which the tensile stress can rise by plastic constraint at high rates of deformation. It intersects the curve of the cleavage strength B (the velocity dependence of which must be smaller than that of Y and should be disregarded for the moment) at the temperature T_c which must be higher than T_t . In other words, it should be possible to obtain cleavage fracture at unusually high temperatures if plastic constraint is produced at high rates of loading. The purpose of the present investigation was to examine this conclusion experimentally. It was found that plastic constraint due to a notch together with high velocity loading could produce cleavage at surprisingly high temperatures. For instance, an ABS Class B ship steel with a 15 ft-lb V-notch Charpy transition temperature of about 10 F, which reaches the maximum Charpy impact work at roughly 100 F, showed the last patches of cleavage fracture just below 200 F in the sharp-notch slow tensile test described below, and just below 300 F in a tension impact test with the same specimen. In what follows, first the experiments will be described, and then their interpretation from the designer's point of view will be discussed.

2. Material and specimens.

Preliminary experiments were carried out with material taken from a plate from the tanker "Ponaganset" which failed in Boston harbor in 1947. The crack in the hull of the tanker ran through this plate. For the final experiments, ship-plate according to the ABS specification Class B was used; it was given by the Bethlehem Steel Company, through the kindness of Mr. S. Epstein, Chief Metallurgist, Bethlehem, and of Mr. Paul Ffield, Chief Metallurgist, Fore River Ship Yard, Quincy, Massachusetts.

In designing the specimen, the aim was to achieve maximum notch constraint and high strain rate effect. The conventional notch impact specimens were obviously out of question, owing to the inferior plastic constraint they can give. They are provided with more or less blunt notch tips with specified radii of curvature; this originated from a confusion between plastic constraint and elastic stress concentration. In a completely brittle material, the stress concentration is inversely proportional to the square root of the notch tip radius; it becomes not only very high but also uncontrollable if the radius is made too small to be reproduced accurately. This was the reason for the choice of moderate notch tip radii. In reality, however, the tensile stress at the surface of the notch tip cannot rise above the uniaxial yield stress Y in a ductile material, no matter how sharp the notch; the highest tensile stress occurs a little farther away from the tip, and it can never rise above a theoretical maximum of 2.5 or 3, no matter how sharp the tip. In order to obtain maximum constraint and best

representation of the most unfavorable conditions that may arise in practice, therefore, the notch must be made as sharp and as similar to a crack as feasible. Moreover, it must extend over the entire circumference of the specimen, not only over one of its sides. To increase the rate of plastic deformation at the notch tip as far as is possible with impact machines of usual design, tension instead of bending was used; for obvious geometrical reasons, this increases the local strain rate by a factor of order 10 compared with the usual Charpy or Izod specimens, if a given striking velocity is used. With these points of view, a circumferentially notched round tension impact specimen of design shown in Fig. 2 was chosen. The cylindrical part between the threaded heads has a diameter of $1/2$ in.; in its center, a circumferential saw-cut notch of $1/32$ in. width was machined by a screwhead-slotting saw or a special lathe tool. The bottom of

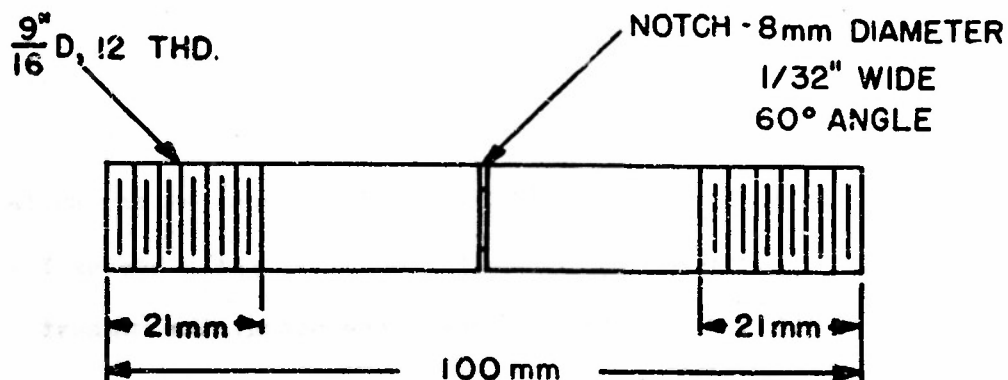


Fig. 2

the saw-cut notch was made sharp in the first case by a special tool or another slotting saw of which the teeth were ground to a 60° V-profile. The notch core diameter was 8 mm; this value was chosen to make the notched sectional area roughly equal to that of the Izod and of the V-notch Charpy specimens.

The tests were performed with a Tinius Olsen impact machine, the striking head of which could be used for both Charpy, Izod, and tension impact tests. The striking velocity was 16.5 ft/sec and the kinetic energy 260 ft-lb. The temperature of the specimen was measured by a copper-constantan thermocouple with potentiometer; the measuring junction was attached to the specimen at the notch. For experiments above room temperature, the specimen was surrounded by a snugly fitting miniature electric furnace consisting of an asbestos paper cylinder on which a nichrome heating coil was wound, covered by a second asbestos paper cylinder. The thermocouple was separated from the inside of the heating furnace by a small mica sheet. For low temperatures, the specimen was cooled by a surrounding wad dipped in a dry ice-alcohol mixture; the wad was removed immediately before the hammer was released. The accompanying V-notch Charpy tests were made with specimens heated or cooled in a nearby furnace or cold-bath and transferred to the impact machine so quickly that no significant temperature change could take place. In the slow tensile tests, the temperatures were produced and measured by conventional means.

Fig. 3 shows results of the preliminary tension impact tests with the "Ponaganset" plate material. A small patch of cleavage fracture is observable in the center of the surface of fracture

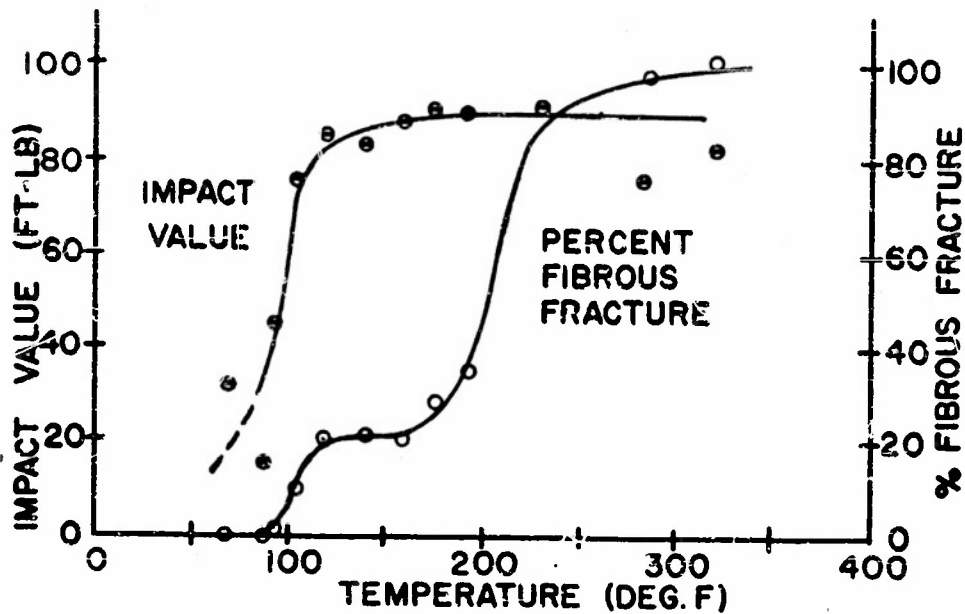


Fig. 3

quite close to 300 F; Fig. 4 shows a fracture surface with a negligible amount of fibrous fracture at 68 F. Fig. 5 shows the appearance of a fracture surface with 29 per cent fibrous fracture at 176 F. The remarkable point is that the impact work reaches its maximum value around 150 F and is quite close to the maximum around 120 F. It drops rapidly at 100 F; measurements between 50 and 100 F show the familiar large scatter. It is interesting that the fibrous-fraction curve levels out below 150 F and then has another sharp dip at 100 F, coinciding with the dip of the impact work curve.

Figures 6 to 11 refer to experiments made with the ABS material. The results of the V-notch Charpy tests are summarized in Fig. 6, in which the upper pair of curves refers to specimens cut in the direction of rolling, and the lower pair to those cut in the transverse direction. Specimens with the notch cut in the plane of the plate show a slightly



Fig. 4



Fig. 5

higher impact value in each group than specimens with the notch perpendicular to the plate. Although the scatter is larger than the difference between the parallel and perpendicularly notched specimens, approximate curves for both sub-groups are indicated. The 15 ft-lb temperature is around 10 F; the maximum of the impact work is reached around 100 F. Figure 7 shows a corresponding plotting of the tension impact tests; here again, the impact work is considerably higher for specimens cut in the direction of rolling than for the transverse specimens. It would have little meaning to compare maximum impact work or 15 ft-lb temperature with those in the Charpy test; the fairest comparison is perhaps that of the maximum and half-maximum temperatures.

The maximum is reached in the Charpy test between 80 and 100 F; in the tension impact test it is less easy to localize, but it would be between 150 and 200 F. Figure 8 shows the percentage of fibrous area in the surface of fracture as a function of the temperature for the tension impact test, and Fig. 9 for the slow notch tension test with the same specimen. The two curves are re-plotted together in Fig. 10. 100 per cent fibrous fracture is reached around 250 F in the impact test and at 200 F in the slow tension test. On the other hand, the last trace of fibrous fracture does not disappear in the slow test until about -100 F, and in the impact test until about 75 F: the difference between the limiting temperatures for complete cleavage is more than three times the corresponding difference between the limiting temperatures for completely fibrous fracture.

Figure 11 corresponds to what was Fig. 3 for the "Ponaganset" steel; it contains the plotting of the impact work and of the fibrous-fraction for the ABS steel. The curves are displaced by about the same amount (100 F) and in the same sense along the temperature axis as in Fig. 3: however, there is no indication of the step visible in Fig. 3 on the fibrous-fraction curve.

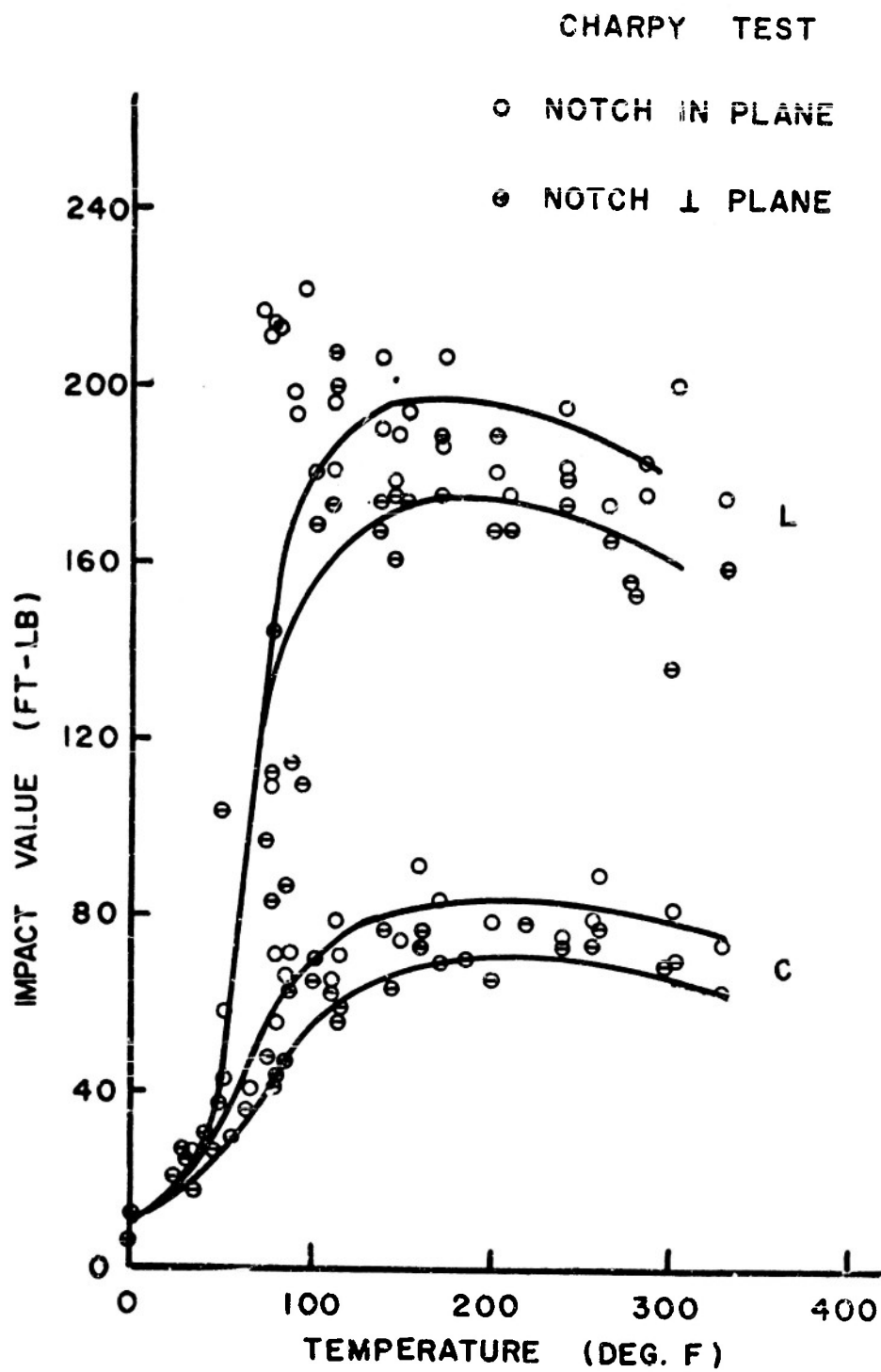


FIG. 6

TENSION IMPACT TEST

○ || DIRECTION OF ROLLING

● ⊥ DIRECTION OF ROLLING

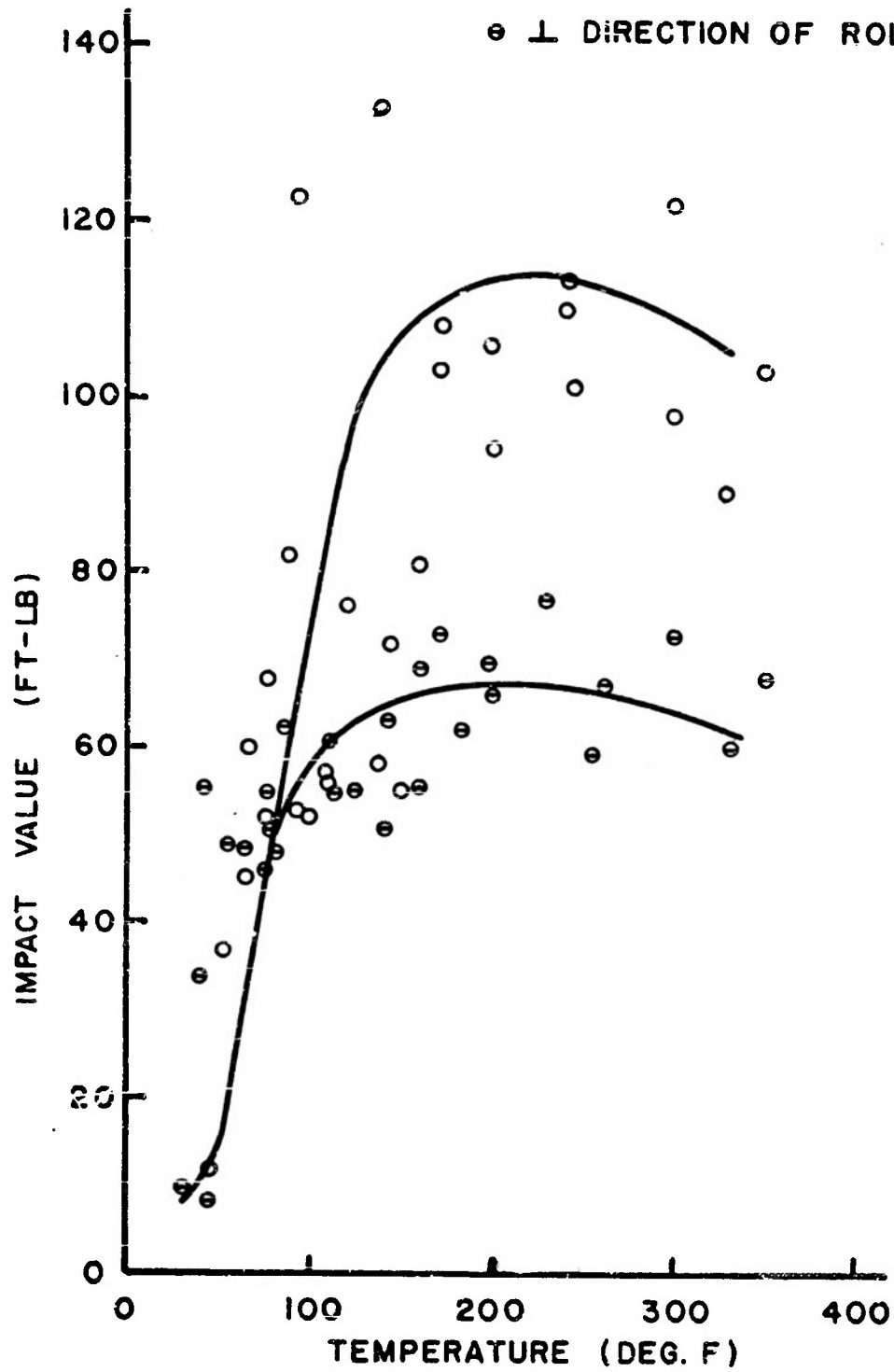


FIG. 7

TENSION IMPACT

PERCENT FIBROUS FRACTURE CURVES

○ || DIRECTION OF ROLLING

⊙ ⊥ DIRECTION OF ROLLING

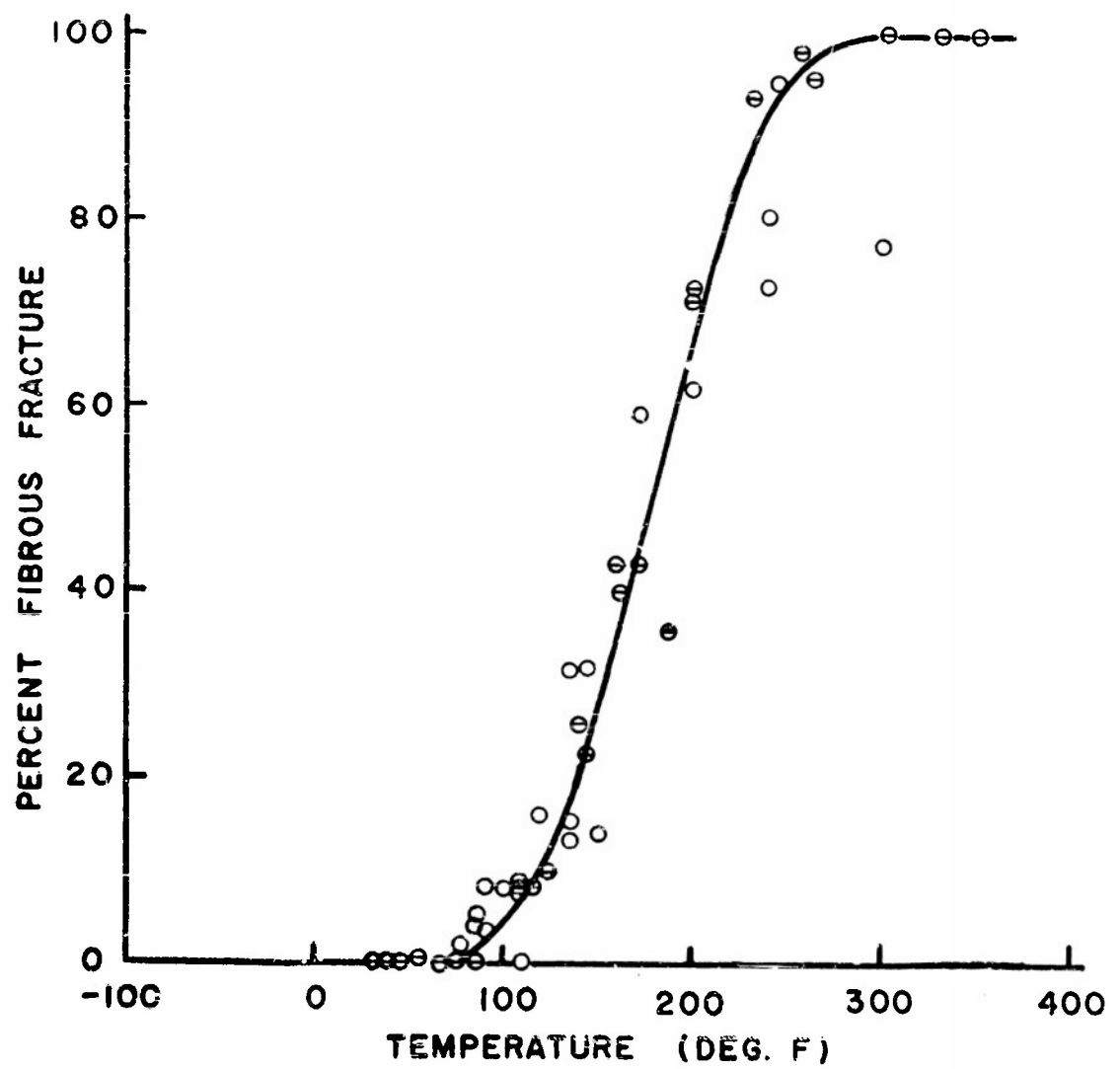


FIG. 8

SLOW TENSION

PERCENT FIBROUS FRACTURE CURVES

○ || DIRECTION OF ROLLING

● ⊥ DIRECTION OF ROLLING

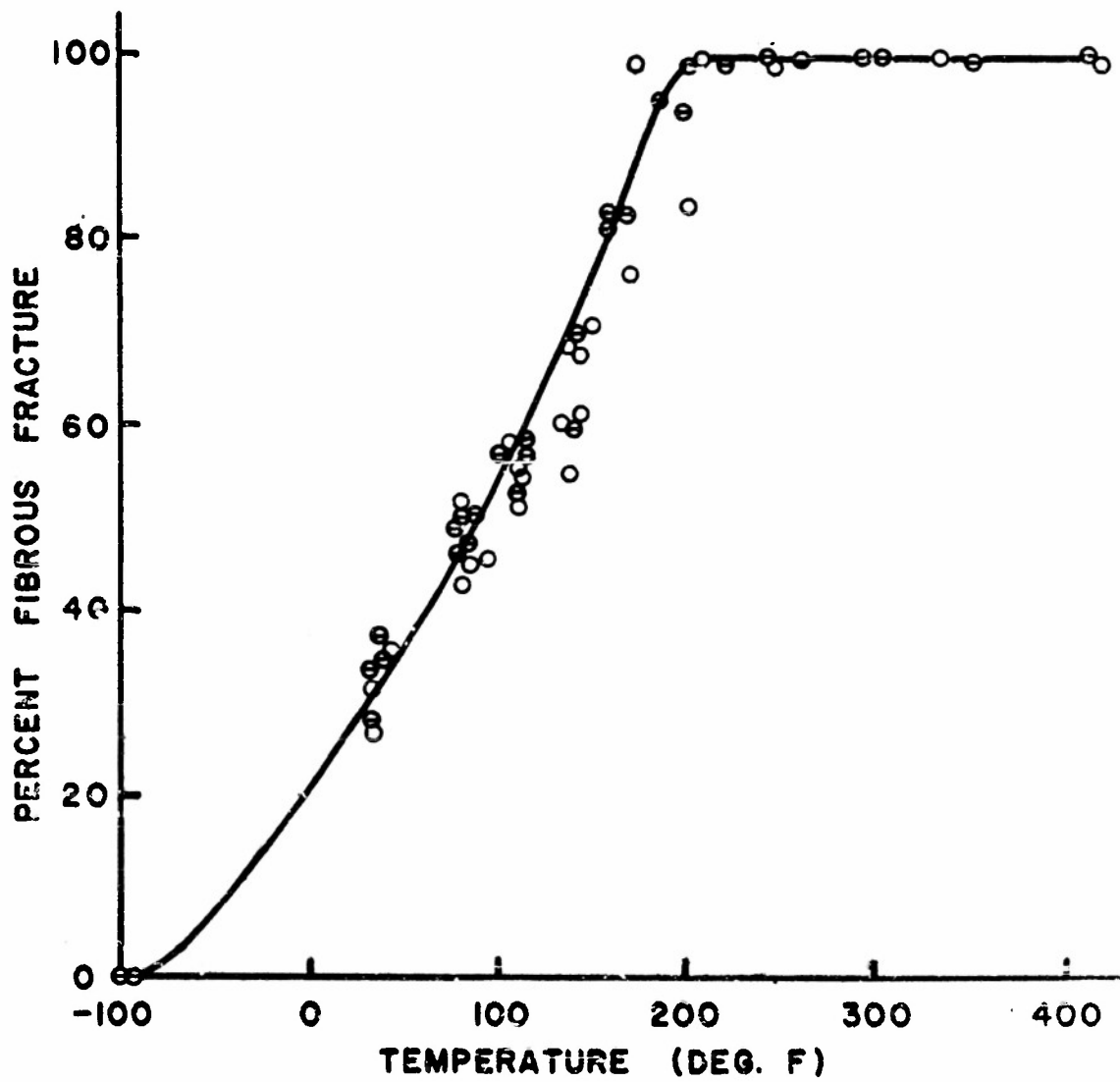


FIG. 9

SLOW TENSION AND TENSION IMPACT

PERCENT FIBROUS FRACTURE CURVES

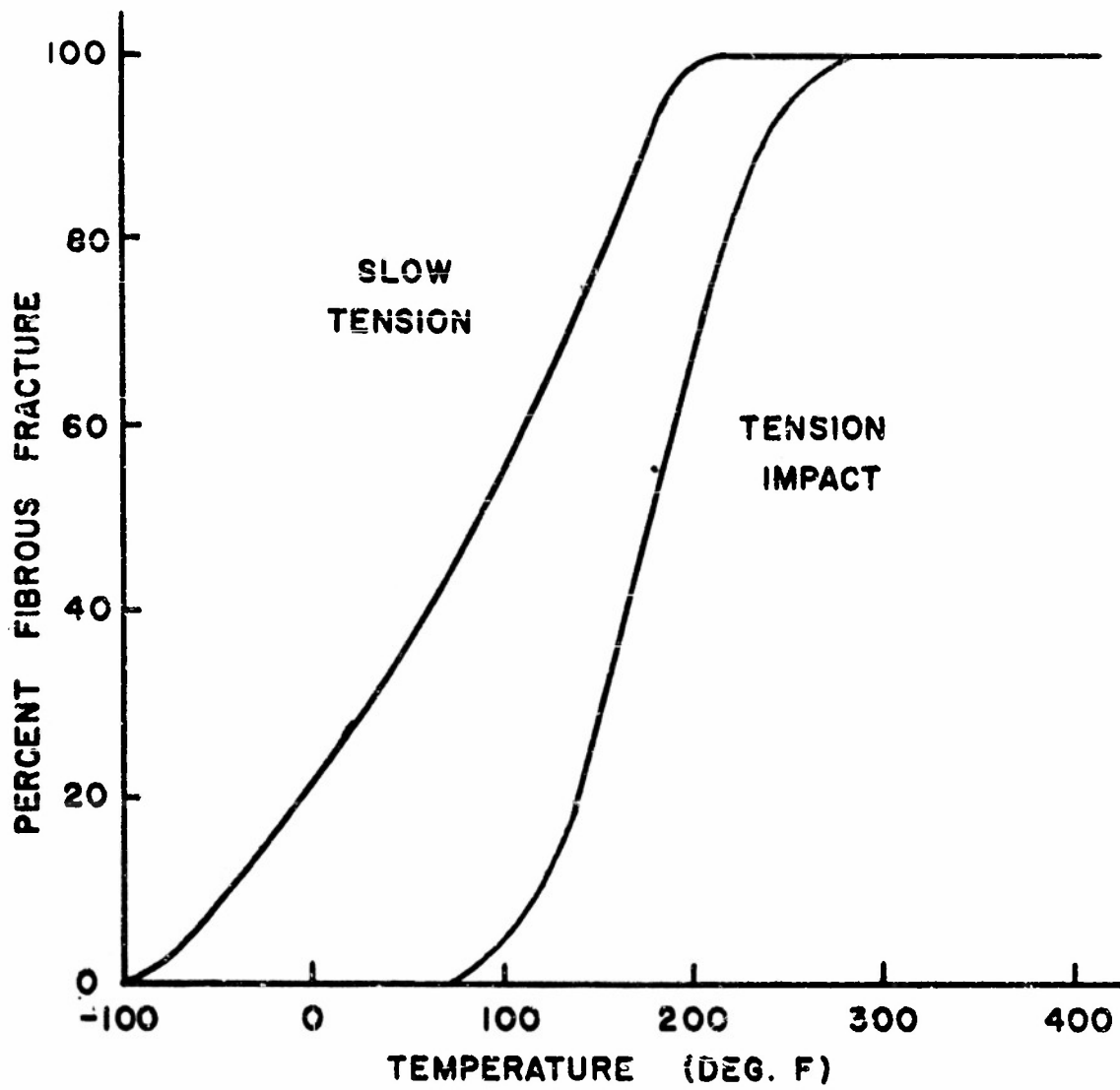


FIG. 10

TENSION IMPACT - IMPACT WORK

AND

PERCENT FIBROUS FRACTURE

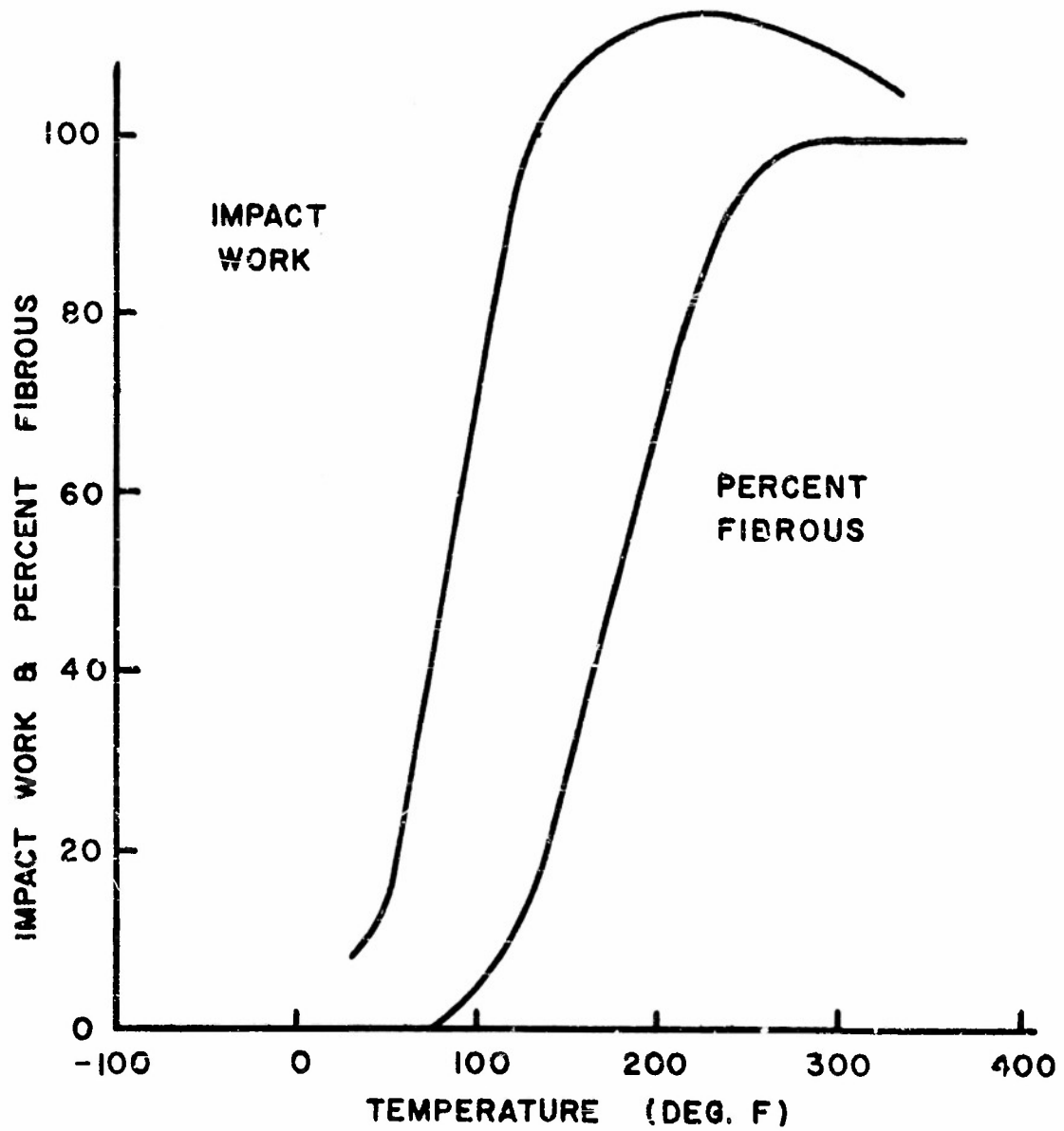


FIG. 11

3. Discussion.

The main results of the experiments can be summed up in the following table.

	Fully cleavage at F.	50% fibrous at F.	Fully fibrous at F.	Half max impact work at F.	Max impact work at F.	10 % max work at F.
Slow notch tension, ABS	-75 to -100	80	200	--	--	--
Tension impact ABS	70 - 75	175	300	75	150-200	45
Charpy, ABS	--	--	--	70	80-100	30
Tension impact "Ponaganset"	80 - 90	200	300	100	120-150	--

The data taken up in the table refer, in the case of the ABS steel, to specimens cut parallel to the rolling direction. It is seen that the difference between the "transition temperatures" based on the impact work in the Charpy and the tension impact tests is not very great: the temperature at which 10 per cent of the maximum impact work is present is about 15 F higher in the tension impact test. The temperatures at which the maximum impact work is nearly reached are more widely apart: for the Charpy, it lies somewhere between 80 F and 100 F, for the tension impact test between 150 F and 200 F. It should be noted that the maximum in the Charpy test is almost twice as high (about 200 ft-lb) as in the tension test (about 110 ft-lb).

Quite striking is the difference between the slow and fast tension tests. The temperatures at which 100 per cent and 50 per cent fibrous fracture respectively are present are 100 F higher in

the impact test than in the slow tension test; the temperature at which fully cleavage fracture appears is rather more than 150 F lower in the slow tension test. This is an impressive demonstration of the importance of the velocity effect.

It is surprising that the last trace of cleavage fracture in the tension impact specimens does not disappear until the temperature has reached about 300 F; in this respect, there is no clear difference between the brittle steel of the "Ponaganset" and the manganese-rich new ABS steel. Similarly, there is no significant difference between the two steels in the temperature below which completely cleavage type fracture is present. The considerable difference between them appears only in the position of the low-temperature tail of the impact energy curve.

The experiments confirm the assumption that cleavage fracture at remarkably high temperatures can be produced by superposing high notch constraint upon high velocity of straining. Does this indicate that low carbon steels are potentially capable of brittle fracture at unsuspectedly high temperatures? Obviously, not. If a strong notch constraint is present, the material has to undergo correspondingly high amounts of plastic deformation, and then the fracture is no longer brittle, although it may be prevalently of the cleavage type. This is illustrated by Fig. 3 where the impact work is still close to the maximum when the area of fracture is 30 per cent cleavage. In the case of the ABS steel, Fig. 11 shows that when 90 per cent of the surface is of the cleavage type, the impact work is still above 80 per cent of its maximum value.

This is not surprising: most, or practically all, of the impact work is spent on plastic deformation before fracture begins. If the notch is inefficient in producing plastic constraint, as in the Charpy and Izod specimens, the temperature must be fairly low before any cleavage fracture can appear. A highly efficient notch, as in the specimen Fig. 2, on the other hand, can enforce cleavage fracture at higher temperatures, but only at the price of a large amount of plastic deformation needed for preparing the conditions (triaxiality) of cleavage fracture. In such specimens, therefore, the impact work and the fracture appearance transition curves are much wider apart than usual.

Cleavage fractures, at relatively high temperatures, therefore, do not represent much to worry about if they are invariably connected with large amounts of plastic deformation work: in other words, it is brittle fracture, not cleavage fracture, that is a danger in structures. Can the possibility of brittle cleavage fracture be recognized from impact tests? The answer seems to be this. A cleavage fracture is brittle if the crack runs with very little energy consumption and cleavage is enforced by the velocity, not by the triaxiality effect. Unfortunately, the usual impact tests use mainly triaxiality for inducing cleavage: they concentrate on the practically less important effect instead of the decisive velocity effect. That they are nevertheless useful for indicating the tendency of a material for brittle cleavage fracture seems to be due to the remarkable coincidence that plastic constraint and high strain rates are roughly equally powerful in raising the tensile stress⁽⁶⁾: both can apparently increase it up to about 2 or 3 times the low-velocity uniaxial tensile yield stress.

For this reason, as Fig. 1 shows, they produce roughly similar transition temperatures if acting individually and so the impact tests in which cleavage is produced mainly by constraint can give a fairly realistic indication of the behavior of the material under service conditions where triaxiality is important mainly in starting the crack, while brittle crack propagation depends essentially on the velocity effect.

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