MI-12 THE EFFECT OF SMALL DRILLED HOLES OF THE NOTCH TOUGHNESS OF IRON BASE ALLOYS

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## ABSTRACT

The influence of two drilled holes on the notch toughness of some iron base alloys was investigated by means of impact and slow bend testing. The impact transition temperature of drilled specimens was found to be substantially lower than that of standard V notch specimens. In addition, the load carrying capacity of drilled specimens is also greater than that of standard specimens at low temperatures where both types of specimen fracture by cleavage. The impact energy required to produce low energy tear fracture in an ultra high strength steel is doubled when drilled holes are present. Substantial improvements in notch toughness are also noted when holes are drilled partways through the thickness. One small hole placed at or in front of the notch tip produces no significant improvement in notch toughness.

Metallographic examination of etch pitted specimens of iron silicon revealed that the holes caused a redistribution of root strain. This effect, coupled with a decrease in plastic stress concentration factor of the notch, accounts for the improvement in notch toughness. The optimum geometrical configuration of the holes was determined. It was shown that holes produce the largest beneficial effects when they lie in the yield zones that emanate from the notch and when the holes are close to the notch.

## INTRODUCTION

The cleavage fracture stress of an unnotched, polycrystalline, BCC metal, $\sigma_f$, is the stress required to cause unstable propagation of microcracks that are formed by plastic deformation (1,2). For a metal having constant grain size, there is a ductility transition temperature $T_D$ below which the yield stress $\sigma_Y$ is greater than $\sigma_f$ so that fracture occurs upon yielding. At temperatures above $T_D$, $\sigma_Y$ is less than $\sigma_f$ so that some strain hardening

$$\Delta\sigma = \epsilon_f \frac{d\sigma}{d\epsilon} = \sigma_f - \sigma_Y$$

occurs before fracture. Consequently, the tensile ductility $\epsilon_f$, is given by the relation (2)

$$\epsilon_f = \frac{\sigma_f - \sigma_Y}{d\sigma/d\epsilon} \qquad (1)$$

In BCC metals $\sigma_Y$ decreases sharply with increasing temperature so that $\epsilon_f$ increases with increasing temperatures above $T_D$, at a rate determined by the temperature dependence of $\sigma_f$ and $d\sigma/d\epsilon$, as well as by $\sigma_Y$. At high temperatures the strain at which ductile fracture initiates $\epsilon_f'$, is less than $\epsilon_f$ so that the initiation mode changes from brittle to ductile.

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In thick specimens containing an external notch of depth $c$ and tip radius $\rho$, yielding begins locally in the form of plastic hinges (3-5) which spread across the specimen to a distance that increases with increasing applied stress and notch depth. General yield of entire notched cross section occurs at a stress $\sigma_{GY}$ when the yield zones have completely spanned the specimen width. Plastic displacements $V(c)$ are produced at the notch tip and they increase with increasing plastic zone size (4-6). For a notch of given depth, cleavage fracture initiates below the notch root at $\sigma = \sigma_F$ when the plastic zone size reaches a critical value (4,7,8) such that $V(c) = V^*(c)$, the critical displacement for fracture initiation. Bilby, et al. have shown (9) that these considerations lead to a form of the Griffith-Orowan and Irwin relations for fracture

$$\sigma_F = \sqrt{\frac{2E\gamma_p}{\Pi c(1-\nu^2)}} = \sqrt{\frac{EG_{IC}}{\Pi c(1-\nu^2)}} \qquad (\sigma_F \ll \sigma_{GY}) \qquad (2)$$

with

$$\gamma_p = \frac{G_{IC}}{2} \simeq \sigma_{GY} V^*(c)$$

Cottrell has shown (8) that $V^*(c)$ can be regarded as the displacement required to initiate cleavage fracture in a miniature tensile specimen, of gauge length $\rho$, ahead of the root. Thus $V^*(c) = \epsilon_f \rho$, and notch toughness increases with tensile ductility.

At a given temperature, the tensile ductility of the "miniature specimen" will be different from that given by equ. (1) for primarily two reasons. First, because the higher local strain rate (4,10) at the tip raises $\sigma_Y$ up to $\sigma_Y^*$ and second, because the plastic constraint produced in thick plates raises the maximum tensile stress in the plastic zone from the tensile yield stress $\sigma_Y^*$ up to $\sigma^{max} = K_{\sigma(p)} \sigma_Y^*$.

$K_{\sigma(p)}$ is a function of specimen and notch geometry and the amount of local strain at the notch tip (4,10). It increases from a value of unity at the onset of local yielding up to a maximum value $1/\beta$, at general yield in Charpy V notch specimens. Neglecting the small amount of strain hardening that occurs in the root prior to general yield, the fracture criterion becomes

$$K_{\sigma(p)} \sigma_Y^* = \sigma_f \qquad \sigma_F \leq \sigma_{GY} \qquad (3)$$

where $K_{\sigma(p)}$ increases with $V(c)$. Thus, increasing the ratio $(\sigma_f/\sigma_Y^*)$, (e.g., by raising the temperature) raises the value of $V^*(c)$ that is required for fracture and hence the value of the nominal $\sigma_F$. The nil-ductility temperature $T_{D(N)} < T_D$ is approximately the temperature at which $\sigma_F = \sigma_{GY}$.





At higher temperatures, plastic constraint alone is not sufficient to raise the local tensile stresses in the plastic zone up to $\sigma_f$, and some strain hardening in the root is required (4). Fracture occurs after general yield, at a root displacement

$$V^*(c) = \rho\epsilon_f = \rho \left( \frac{\sigma_f - \frac{1}{\beta}\sigma_Y^*}{\frac{1}{\beta}\frac{d\sigma}{d\varepsilon}} \right) \qquad (4)$$

At a much higher temperature $\epsilon_f' < \epsilon_f$, and fracture initiates in a ductile manner. Similarly, in a notch impact test, the impact energy begins to increase markedly (11) at a temperature $T_{S(N)}$ where $\epsilon_f > \epsilon_f'$.

This brief discussion indicates that notch toughness is primarily related to the difference between the intrinsic fracture stress and the yield stress. Thus, even if $\sigma_f$ is very high, say 500,000 psi, the notch toughness of an ultra high strength steel ($\sigma_Y \simeq$ 250,000 psi) will be low for a typical value (12) of $1/\beta \cong 2$. As Cottrell has emphasized,(13), a high notch toughness and high load carrying capacity can only be achieved if some means are available for relaxing tri-axial atresses, and lowering $1/\beta$, at the root of a crack or notch. This is possible in anisotropic materials, such as fiber composites (14,15) or wrought alloys (16,17), when tensile loads are applied in the fiber direction, and the notch plane is perpendicular to the fibers. The transverse stresses set up in the plastic zone are able to crack the relatively weak fiber-matrix interfaces (13-15), relaxing plastic constraint, and this improves the notch toughness considerably. Similarly, in extruded compacts of $Al_2O_3$ dispersed in AgCl, fibrous cracks develop from particle-matrix interface separation (18) and the reduction in constraint is able to lower the impact transition temperature by more than 70°C, as compared to that of pure AgCl.

The present study was undertaken to determine whether small holes, introduced by mechanical drilling, could similarly improve the notch toughness of mild steel at low temperatures. It will be shown that marked improvements in notch impact and notch bend properties are possible by appropriately drilling two holes around the notch. Improvements in tear energy absorption were also noted for an ultra high strength maraging steel. This paper defines the relevant geometric parameters which produce the optimum improvement in toughness and shows how the intrinsic ductility of the material also affects the improvement of properties that result from the introduction of the holes.

## EXPERIMENTAL PROCEDURE

Standard Charpy V notch impact specimens were machined out of a hot rolled plate of a low carbon nickel iron (Table # 1) such that the notch was transverse to the rolling direction.

Metallographic examination revealed that this steel contained nearly an equiaxied microstructure. Grain boundary carbides were present over 10-20% of the ferrite boundary area.

Table # 1

| Heat No. | C | Mn | P | Si | S | Ni | Grain Size |
|---|---|---|---|---|---|---|---|
| V906 | 0.02 | 0.22 | 0.002 | 0.24 | 0.006 | 2.14 | 0.00110 |
| Fe-Si | 0.007 | --- | --- | 3.25 | --- | --- | 0.00200 |

Specimens used in slow notch bend tests were machined in the same manner as the standard Charpy specimens, with the addition of three grooves for the positioning of the loading rollers (Figure 1a). In addition, some four point bend studies were performed on a well annealed, etch-pittable iron-3% silicon alloy to directly observe the interaction of the plastic hinges and the holes. The specimens used in this investigation are shown in Figure 1b. After loading, the specimens were aged 20 minutes at 160°C, polished mechanically and electrolytically, and electro-etched in the standard chrome-acetic acid solution (19) to reveal dislocation arrays (20). All slow bend tests were performed on an Instron testing machine at a cross head velocity of 0.08"/min. A specially constructed bend jig and cryostat maintained the specimens at temperatures between -196°C and room temperature within ± 1°C.

Cylindrical holes were alligned and drilled mechanically using a "Jig Bore." This machine was equipped with an optical device which enabled the holes to be positioned within ± 0.001". The position of the holes, relative to the notch tip, is described by the coordinates $(R,\theta)$ shown in Figure 1c. All holes were 0.0292" in diameter and were drilled completely through the specimen thickness unless otherwise stated.

## EXPERIMENTAL RESULTS

The standard Charpy impact curve of the very low carbon, iron nickel alloy showed a sharp rise in energy over a narrow temperature range (4°C) so that the 50% transition temperature $T_{S(N)}$ was well defined at -58°C. This sharp rise is characteristic of clean, essentially single phase materials, such as 0.02% carbon steels. Observation of the fracture specimens indicated that general yield occurred prior to cleavage fracture at temperatures well below $T_{S(N)}$. Above $T_{S(N)}$, the specimens did not fracture but simply wrapped around the impact hammer. This sharp transition behavior facilitated the evaluation of the effect of drilled holes on impact properties.

<u>One hole</u> 0.0292" in diameter was drilled directly beneath the notch tip $(\theta = 0°)$ at distances R ranging from 0.010" (keyhole type specimen) to R = 0.070". As shown in Figure 2, the presence of the one hole did not cause any appreciable change in the transition temperature, even when it was placed at the notch tip. This result is not in conflict with differences that have been reported (21) for transition temperatures obtained in V notch and keyhole specimens. In the present work, the "keyhole" sample has a tip radius of 0.0145", only 50% greater than the standard V notch. On the other hand, the standard keyhole specimen has a considerably larger radius (0.0395") and would be expected to appreciably lower the transition temperature.





When <u>two holes</u> were drilled symmetrically about the plane of the V notch, a <u>substantial</u> lowering of the transition temperature was achieved. As shown in Figure 3, the transition temperature can be lowered by 33°C (i.e., down to -91°C) in this alloy for R = 0.0448", $\theta = 75°$. Figure 4 shows the appearance of the standard Charpy specimen and a drilled specimen after impact at -88°C, 30°C below the standard transition temperature. While the standard samples fractured entirely by cleavage, the large amount of fibrous tearing in the drilled specimens has completely prevented the initiation of cleavage, and the specimens absorb the maximum 240 ft lb impact without breaking. At temperatures approximately equal to the transition temperature of the drilled samples, a dynamic cleavage crack sometimes initiated after 50% fibrous tearing and intermediate energy absorption is observed (Figure 3). The Charpy curves for all variations of $\theta$ are parallel to the standard curve.

At lower temperatures $(T < -95°C)$, even drilled specimens fracture by cleavage. This occurs in one of two possible ways. (1) A fibrous crack forms between the notch and one hole and runs into this hole. Subsequently, a dynamic cleavage crack is nucleated near this same hole and causes complete separation of the specimen. The other hole is essentially unaffected by these processes. (2) Cleavage fracture is nucleated directly ahead of the notch tip and propagates between the holes. Neither hole is affected and the fracture appearance is the same as in the standard specimens. In either case, the total energy absorbed is quite low. Low test temperatures and large $\theta$ or R values favor process (2) rather than (1). Cleavage fracture initiated from one hole is favored when R and $\theta$ are small and the fracture strain (and hence the temperature) is relatively high.

The effects of varying values of R and $\theta$ on the impact transition temperatures are summarized in Figure 5. At a constant value of R = 0.0448", substantial lowering of the transition temperature was obtained when $\theta$ was varied between 45 and 80°, with optimum conditions achieved at $\theta = 75°$.

Since one hole drilled at the root (R = 0.01") has little effect on impact properties, whereas two holes at R = 0.0448" can lower the transition temperature by about 30°C, the impact transition temperature initially decreases with increasing values of R between these two values. However, when R increases from 0.0448" up to 0.074", at $\theta = 45°$, then the transition temperature rises, as shown along the line AB in Figure 5. Consequently, there is an optimum hole configuration for lowering the transition temperature, which occurs when R = 0.0448" and $\theta = 75°$.

To investigate whether beneficial effects could be obtained if holes were drilled <u>only partways through the thickness</u> a series of holes were drilled at the optimum geometry to a <u>total depth</u> of 1/3, 2/3, and 5/6 of the thickness. The holes were drilled symmetrically about the mid-thickness (i.e., the 1/3 thickness hole was drilled 1/6 of the thickness from each face so that two holes appeared at the optimum geometry on each face). For comparison, another series was drilled to 2/3 of the total thickness entirely from one face. For each series of specimens, the impact energy increased sharply at the transition temperature, which varied with the drill depth as shown in Figure 6. Drilling through 5/12 of the thickness from each side (5/6 total depth) is required to achieve the optimum reduction in transition temperature of 33°C. Drilling 1/3 of the thickness from each side (2/3 total depth) produces only a 10°C lowering of transition temperature and drilling 1/6 of the thickness from each side (1/3 total depth) produces no improvement at all. However, the optimum improvement is obtained when 2/3 of the total thickness is drilled from one side.

In order to determine whether the beneficial effects of drilled holes could be realized in other alloy systems, specifically those in which the amount of second phase (e.g., carbides) is greater and the impact curves rise more gradually, a few experiments were carried out on a hot rolled 2% nickel steel containing 0.1% carbon. About 20% of the microstructure was pearlite and large amounts of semi-continuous carbides were present at ferrite grain boundaries.

Although an insufficient supply of material prevented our obtaining complete impact curves for standard and fully drilled samples (R = 0.0448", $\theta$ = 60°), preliminary results indicate that the 50% fibrous appearance temperature can be lowered by 55°C by the presence of the two holes. 90 ft lb were absorbed in the fracture. At this same temperature, the standard charpy specimen absorbed only 5 ft lb and fractured completely by cleavage. Thus, it appears that drilled holes can produce a substantial improvement in the toughness of notched specimens of mild steel used for structural applications.

250 grade maraging steel[2] fractures by low energy tear (22) at -196°C and room temperature, absorbing 14 and 18 ft lb respectively. Consequently, there is no "transition temperature" at which the toughness increases rapidly as there is in the low strength alloys. However, when two holes were drilled at optimum geometry, the impact energy increased to 34 and 37 ft lb at these two temperatures. Fracture consisted of fibrous tearing from the sides of the notch to both holes with final separation occurring when a new crack initiated one of the holes and propagated through the specimen. The bend angle at fracture was about 5° when holes were present but less than 2° in the standard charpy sample.

Improvements in the strength of notched specimens of iron-3% silicon tested under slow bend conditions, have also been noted (23). Thus, it appears that the beneficial effect of holes in notched specimens is a general one and is not restricted to the low carbon alloy used in the majority of this investigation.

In order to better understand the reasons for the striking reduction in the impact transition temperature, due to the presence of drilled holes, slow bend tests in three point loading were carried out on standard and drilled charpy specimens of the standard 0.02% carbon alloy. The results for the standard sample and those drilled at $\theta$ = 75°, R = 0.448" are summarized in Figures 7 through 9. The behavior of standard samples is similar to that observed by Knott and Cottrell (4) in low carbon, high nitrogen iron. The lack of a large rise in fracture load that is observed in pearlitic steel (24) when fracture occurs after general yield is believed to result from the low strain hardening rate in this alloy.

There are several important effects produced by the two holes.

(1) General yield is reached at a lower load over the entire transition temperature range (Figure 7).

[2] Obtained through the courtesy of the Lockheed Missiles and Space Company Laboratory.





(2) There is an approximately 20°C range during which the standard fracture by cleavage at bendangles below 5°, but the drilled samples do not fracture at the maximum bend angle (24°) permitted by the bend jig. Figure 9 shows quite clearly the additional strain required for fracture when two holes are present.

(3) Drilled samples have up to 70% greater load carrying capacity than standard samples at low temperatures where both standard and drilled samples are brittle and fracture by cleavage, before or at general yield (Figure 8). In these cases fracture does not have to occur between the notch and the holes for the improvement to be achieved. At high temperatures, where fracture did not occur, the ultimate load carrying capacity of the drilled samples was somewhat lower than that of the undrilled specimens.

To observe directly the effect of drilled holes upon the initial yielding at the notch root, standard and drilled samples (R = 0.0448", $\theta$ = 75°) of an Fe-3% Si alloy were loaded at room temperature in four point bending to various fractions of their respective general yield loads. The yield zones were revealed by dislocation etch-pitting. A comparison of the yield zones, with and without holes, at 50, 75 and 98% of general yield is shown in Figure 10.

A comparison of Figure 10a and 10b shows that initial deformation is concentrated at the notch tip in the standard sample ($\sigma/\sigma_{GY}$ = 50%), but in drilled samples the deformation is increased in the region above and below the notch (i.e., between the notch and the holes). At $\sigma/\sigma_{GY}$ = 75% (Figure 10c,d), the holes have caused heavy deformation between the holes and the side of the notch while preventing any increase in strain directly at the notch tip. Strains in the standard sample are more localized near the notch tip.

At $\sigma/\sigma_{GY}$ = 98% (Figure 10e,f), the yield zones have nearly traversed the entire sample. As shown in Figure 11, there is such a high concentration of strain between the side of the notch and the holes in drilled samples that etch pits are not observed (due to an insufficient carbon concentration (25) for decoration of the high dislocation density). Since the strain distribution has been modified by the presence of the holes, the strains in front of the notch are less than the value of 10% found (4) in standard samples at general yield. In the standard sample, on the other hand, the maximum strain is directly in front of the notch tip and can still be observed. These micrographs indicate that the holes are redistributing the maximum local strains and corresponding local stresses in the plastic zone.

## DISCUSSION

The marked improvement that occurs in impact properties when two holes are drilled near the crack tip appears to result from the process shown schematically in Figure 12. The strain concentration at the side of the notch causes a fibrous crack to extend from the notch sides to both of the holes (Figure 12b). The notch now has two tips, in the form of elongated holes, that are removed from the plane of minimum cross section and maximum tri-axial constraint (Figure 12c). Under the bending stresses produced by the impact hammer, the —< shaped notch continues to open up, causing the effective tip radii (i.e., the radii of the two holes) to increase still further (Figure 12d). Still large strains may initiate a fibrous tear fracture from either or both blunted holes (see Figure 4a), but these tears cannot propagate in the low carbon alloy. Consequently, the two criteria for lowering the impact transition temperature are that 1) cracking occurs from the notch to both holes before a cleavage crack is formed ahead of the notch, in the region of high constraint and 2) that once a crack spreads from the notch to a hole, fracture does not initiate on the opposite side of the hole (i.e., at point A, Figure 12b). Criterion (1) can be written as

$$V^*_H(c) < V^{**}(c) \tag{5}$$

where $V^*_H(c)$ is the critical tip displacement at which a crack runs from the side of the notch to a hole and

$$V^{**}(c) = \alpha\, \rho\, \epsilon_f = \alpha\, \rho \left( \frac{\sigma_f - \frac{1}{\beta}\sigma^*_f}{\frac{1}{\beta}\frac{d\sigma}{d\epsilon}} \right) \tag{6}$$

is the critical tip displacement at which a cleavage fracture will be initiated ahead of the notch. Equation (6) is similar to equation (4), except for the factor $\alpha > 1$ which is a measure of the redistribution of strain at the notch tip when holes are present. That is, the redistribution of strain shown in Figure 10 increases the effective gauge length of the "tensile specimen" ahead of the notch and increases the displacement required to reach the cleavage fracture strain $\epsilon_f$.

Criterion (1) will be more easily satisfied when the presence of holes is able to lower the value of the plastic stress concentration factor ($K_{\sigma(p)}$ below general yield and $1/\beta$ at or above general yield) since this will increase $V^{**}(c)$. That holes are able to do this is evidence by the fact that the fracture load of drilled samples is considerably greater than that of undrilled samples, at low temperatures (Figure 8) where fracture does not initiate to the holes and both drilled and undrilled samples fracture completely by cleavage. The decrease in plastic stress concentration factor may result from the fact that under loading compressive stresses are set up at the bottom of the holes (i.e., at point B, Figure 12) and the compressive stress field reduces the maximum tensile stresses produced ahead of the notch. It may also result from a general decrease in the plastic constraint set up by the notch. That this may occur is seen from the fact that the general yield load of drilled samples is less than that of standard samples (Figure 7), as is the ultimate load at high temperatures (Figure 8) where drilled and standard samples are fully ductile. However, since these decreases could also result from the decrease in load bearing cross section (the curved plastic hinge) due to the holes, it is not possible at this time to state to what extent each mechanism contributes to lowering the plastic stress concentration factor.

Similarly, the redistribution of strain from in front of the notch to its side (Figure 11) lowers $V^*_H(c)$ and raises $V^{**}(c)$ (by raising $\alpha$). Both of these effects enable criterion (1) to be more easily satisfied. The exact mechanism by which the holes redistribute the tip strain has not yet been worked out.





Criterion (2) will be favored if the holes are elongated at the instant that cracks form between them and the notch side becasue then the critical displacement required to initiate cleavage at the hole will be higher. Thus, at temperatures just below the transition temperature of the drilled sample, after cracking has occurred between one hole and the side of the notch, cleavage fracture initiates at that hole, probably within the hole's own plastic hinges (Figure 10d). This occurs before a second crack can develop at the notch and run into the other hole. At or above the transition temperature, the holes themselves will be so elongated that the plastic stress concentration factor at one of them is too low to initiate cleavage fracture before a crack can develop to the other hole. Once cracking occurs to both holes, the relaxation around them becomes so extensive that the blunting mechanism shown in Figure 12 can operate, and fracture is not observed (in the low carbon alloy).

The coordinates R and $\theta$ are important because they determined the nature of redistribution of the local strain at the notch tip and the value of the plastic stress concentration factor $1/\beta$. As shown in Figure 5, the holes positioned at $\theta = 30°$ and $\theta = 90°$ produce significantly smaller decreases in transition temperature than do holes at 45°, 60° and 75°, for R = 0.0448". Green and Hundy have calculated and experimentally observed (3) the position and shape of plastic hinges in a V-notch specimen subjected to three point loading. According to their results, the two holes drilled at 30 and 90° would fall just at the border of the plastic hinges. This implies that a larger value of $V^*_H(c)$ would be required before cracks can develop to the holes and hence that a larger value of $V^{**}(c)$ (i.e., a higher $\epsilon_f$ and hence a higher temperature) will exist before criterion (1) is satisfied. Similarly, when R is increased to 0.074" at $\theta = 30°$ and $\theta = 75°$, the holes are completely outside the yield zones, and equation (5) is not satisfied. As shown in Figure 5, the holes then produce no change in impact transition temperature. Similarly, when one hole is drilled at the notch tip (keyhole specimen) or in front of the notch, this hole does not lie within a yield zone and the transition temperature is unchanged. Thus, a necessary condition for satisfying criterion (1), and hence for lowering the impact transition temperature, is that both holes be drilled within the yield zones of the standard notch.

In addition to lying within the yield zones, the holes must also concentrate sufficient strain between themselves and the notch if they are to: (1) favor criterion (1) by decreasing the value of $V^*_H(c)$ and increasing $V^{**}(c)$ (by lowering $1/\beta$ and raising $\alpha$, equation (6)) and (2) favor criterion (2) by being elongated at the instant a crack runs into them. The strain concentration will be achieved when the holes are placed close to the side of the notch. Thus, at $\theta = 45°$, where all holes lie in the yield zones, increasing values of R beyond 0.0488" results in a transition temperature that approaches that of the standard sample. In other words, the beneficial effect of 0.0292" diameter holes decreases when the holes are placed such that their leading edge is more than one diameter away from the notch tip. Consequently, optimum improvement in notch impact toughness is achieved when the holes lie within the yield zones and are very close to the side of the notch. We have not yet investigated the effect of holes which actually touch the sides of the notch (i.e., when the notch has "ears") or the effect of increased hole diameter.

In slow bend tests the same mechanism operates except that initial cracking to both holes occurs by cleavage rather than fibrous tearing[3] and optimum drilling conditions produced only a 20°C lowering in transition temperature (Figure 9) rather than the 33°C lowering produced under impact conditions. The slow bend transition temperature (about -148°C in standard specimens) is 90°C below that of the impact specimens. This decrease results primarily from the large decrease in $\sigma_Y^*$, and hence the increase in V*(c) at a given temperature, with decreases in loading rate. Under conditions where the standard specimens are tougher it intuitively seemed that the holes would produce an equal or large improvement in notch toughness; the smaller improvement and initial cleavage cracking to the holes was surprising. However, Green and Hundy have shown (3) that the higher strain rate that exists in the impact test produces plastic hinges which are much more inhomogeneous than those produced at the slow rate of straining in a bend test. This implies a lower rate of strain hardening $d\sigma/d\epsilon$ under high strain rates, as reported by Wilshaw and Pratt (26). Since high rates of strain hardening decrease the tendency for fibrous fracture (by making void coalescence more difficult (27,28), thereby raising $\epsilon_f$') and increase the tendency for cleavage fracture (by lowering $\epsilon_f$), it is conceivable that at low temperatures, in the slow bend test, $V_H^*(c)$ is greater for fibrous fractures than for cleavage fractures so that initial cracking to the holes occurs by cleavage. Under impact conditions at higher temperature $V_H^*(c)$ is greater for cleavage fractures than for fibrous fractures (because $d\sigma/d\epsilon$ is lower and cleavage is more difficult), so that initial fracture to the holes occurs by the fibrous mode. Similarly, the lower rate of strain hardening means that criterion (2) (elongated holes when crack run into them) will be more easily met in the impact test than in the slow bend test. Consequently, both criteria will be more easily satisfied under impact loading than in slow bending. Thus, the transition temperature is lowered more when fibrous cracking occurs to the holes than when cleavage occurs to the holes.

This appears to be the case in the 0.02% carbon alloy. Increasing the carbon content up to 0.10% increases the tendency for fibrous cracking and, as mentioned previously, the 50% appearance impact transition temperature can be lowered by 55°C, as compared to 33°C in the 0.02% carbon iron. However, if the tendency towards fibrous cracking is extremely large (e.g., in the maraging steel) then the holes will not be greatly elongated at the time that fibrous cracks are formed between them and the notch; a brittle tear fracture then initiates from one of them, causing complete separation. Although the mechanism shown in Figure 12 is operating, and the impact energy is approximately doubled, criterion (2) is not satisfied so that fracture still occurs. These considerations indicate that the beneficial effects produced by holes depend on the mechanical properties of the particular material, as well as on hole geometry.

In order for optimum improvements in impact toughness to be achieved in partially drilled specimens, V**(c) must be maintained greater than $V_H^*(c)$ in whatever thickness is left undrilled. As shown in Figure 6, partially drilled holes are able to produce the optimum lowering in $T_D$ if the holes are drilled sufficiently deep. Figure 13 shows typical examples of the impacted but unfractured notch (top view of Figure 4a) when holes are drilled partially through the thickness. In all cases, fibrous cracks spread between the notch and the holes over that portion of the thickness where the holes exist, and the undrilled portion of the specimen then fractures primarily by shear rupture. At lower temperature or when shallower holes are

[3] Except at temperatures much above the transition temperature of the drilled specimens.





present, sufficient constraint exists in the undrilled portion of the specimen to allow the nucleation of a cleavage crack, ahead of the notch. This crack propagates forward, in the direction of the notch, and outwards (i.e., towards the sides) and by essentially by-passing the blunted regions is able to cause complete fracture. Under these conditions the holes are relatively ineffective. To a first approximation, the undrilled portion may be considered as a standard sheet sample having a reduced thickness. As the thickness of a sheet decreases, notch toughness increases (24,30-32) because (1) the plastic constraint is relaxed (24), thereby lowering $1/\beta$, and (2) because the relative amount of shear lip in the sheet increases with decreasing thickness (31). Both of these effects can account for the curve shown in Figure 6. In actual practice, the drilled portions of the thickness still contribute somewhat to the plastic constraint. The maximum value of $1/\beta$ for a given depth of drill depends on whther the undrilled portion falls in the specimen center or at the surface. Figure 6 shows that a total hole depth of 2/3 total thickness is more effective when the hole is drilled from one side and the undrilled portion extends out to the side surface, than when the undrilled portion is bounded on both sides.

The practical implications of this investigation are that small holes can be used to reduce the embrittling effect of incipient cracks that form during service (e.g., by fatigue, corrosion) or design notches (e.g., keyways). The shape of the plastic hinges could be experimentally determined for any particular notch geometry in model specimens of iron-3% silicon (or iron-nitrogen in which plastic hinges can also be revealed by etching (3)) and the holes could then be appropriately placed, in accordance with considerations described here.

## SUMMARY

1. Two small holes, mechanically drilled near the tip of a notch, are able to:
   a) substantially decrease the ductile-brittle transition temperature in mild steels
   b) substantially increase load carrying capacity at very low temperatures where both drilled and standard specimens fracture by cleavage
   c) substantially increase the impact energy required to produce low energy tear fracture in an ultra-high strength steel.
2. To produce these improvements, the holes must lie within the plastic hinges which form in the notched specimen. Consequently, one small hole placed at or in front of the notch tip produces no significant improvement in notch toughness.
3. The improvement produced by the presence of two holes is a function of the coordinates of the holes, relative to the notch tip. In addition to lying within the yield zones, the holes should also be close to the notch tip. Optimum improvements in notch toughness were achieved in the present experiments when the 0.0292" diameter holes were placed directly above and below the V notch, one hole diameter away from the tip ($\theta = 75°$, $R = 0.0448"$).

4. These effects can be explained in terms of the redistribution of strain at the notch tip and the lowering of the plastic stress concentration factor, when holes are present.

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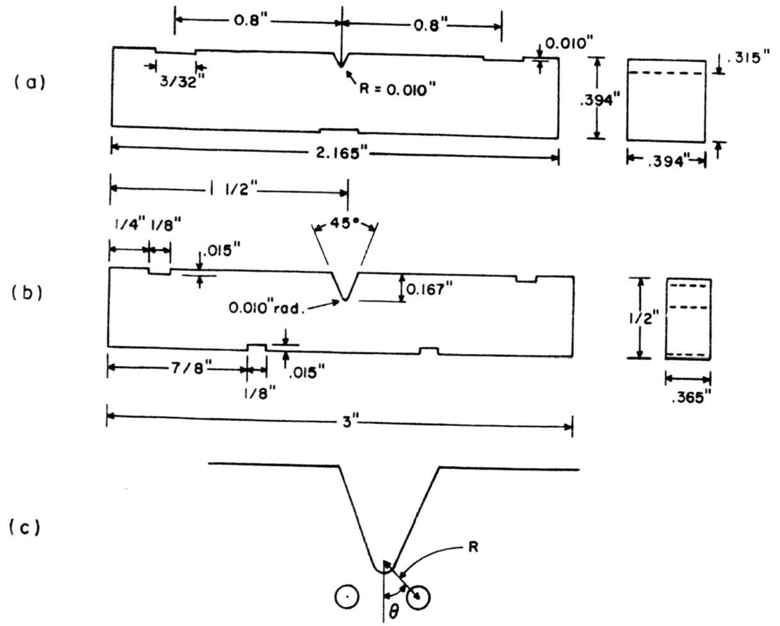


Figure 1. Schematic diagram of slow bend specimens and coordinants of drilled holes
(a) Three point loading
(b) Four point loading
(c) Coordinants of drilled holes

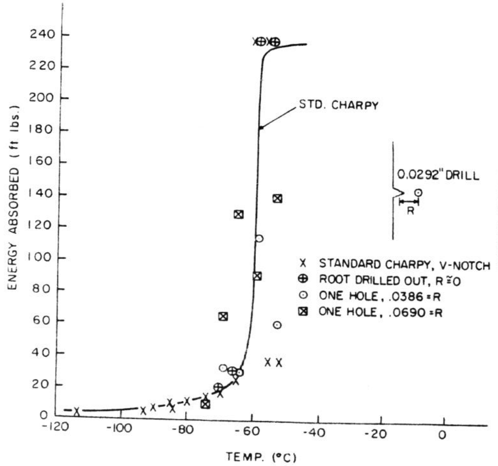


Figure 2. The effect of one 0.0292" diameter hole drilled at various distances in front of the notch tip on the charpy impact curve of the low carbon iron nickel alloys.

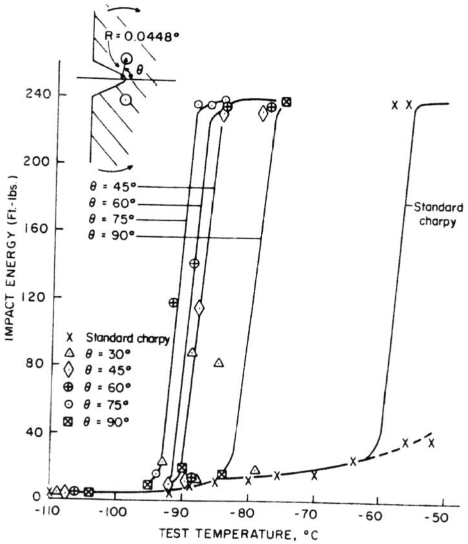


Figure 3. The effect of two 0.0292" diameter holes drilled at various distances in front of the notch tip on the charpy impact curves of two iron-nickel-carbon alloys.





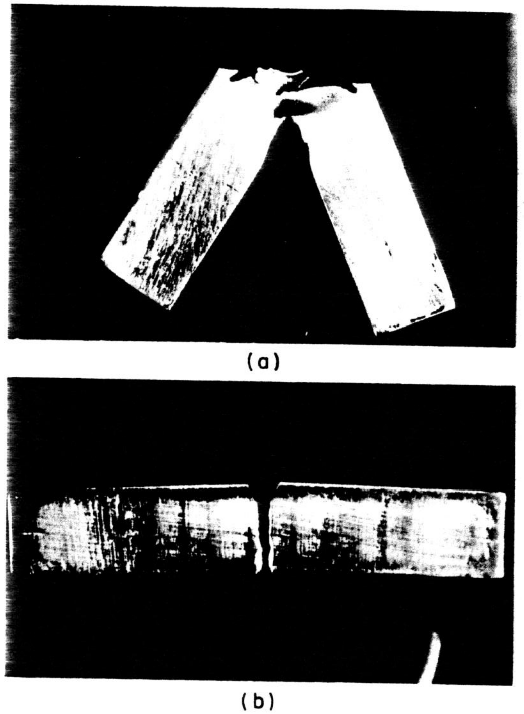


Figure 4. Charpy samples after impact at -88°C
[30°C below the normal transition temperature]
(a) Two drilled holes [θ = 60°; R = 0.0448"] present
(b) Standard charpy specimen

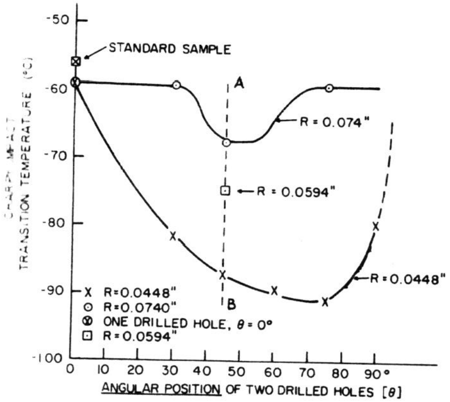


Figure 5. The effect of varying the angular coordinant (θ) of the two drilled holes on the impact transition temperature of low carbon, nickel iron.

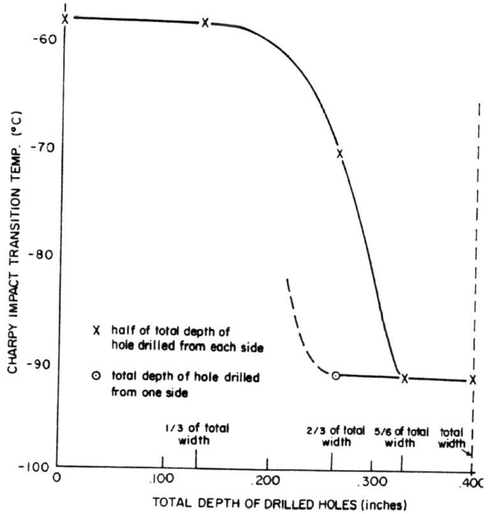


Figure 6. The effect of two holes (R = 0.0448"; θ = 75°) drilled to various fractions of the total thickness on the impact transition temperature of low carbon, nickel iron.

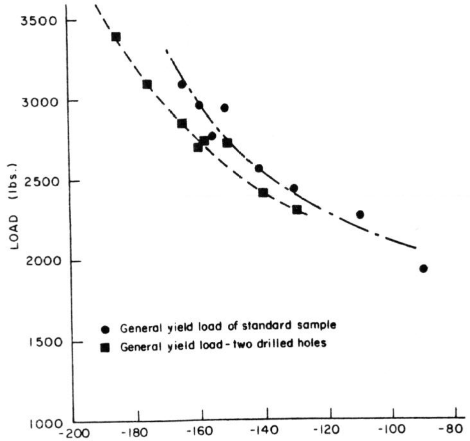


Figure 7. The effect of two holes (R = 0.0448", θ = 75°) on the general yield load as a function of temperature in low carbon, nickel iron loaded in three point bending.

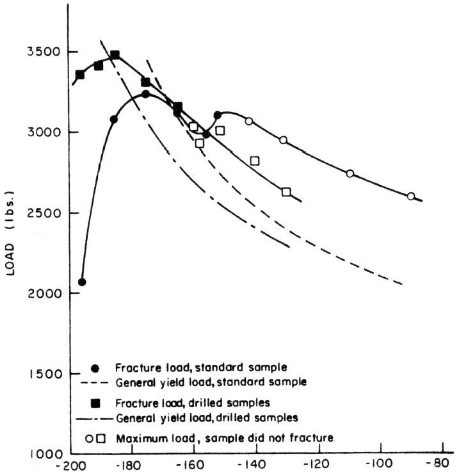


Figure 8. The effect of two holes (R = 0.0448"; θ = 75°) on the fracture load as a function of temperature in low carbon, nickel iron loaded in three point bending.

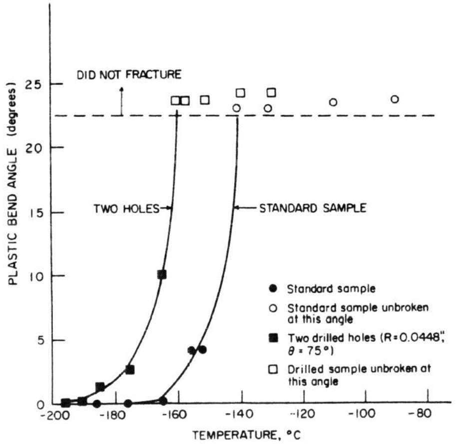


Figure 9. The effect of two holes (R = 0.0448"; θ = 75°) on the plastic bend angle at fracture as a function of temperature in low carbon, nickel iron loaded in three point bending.





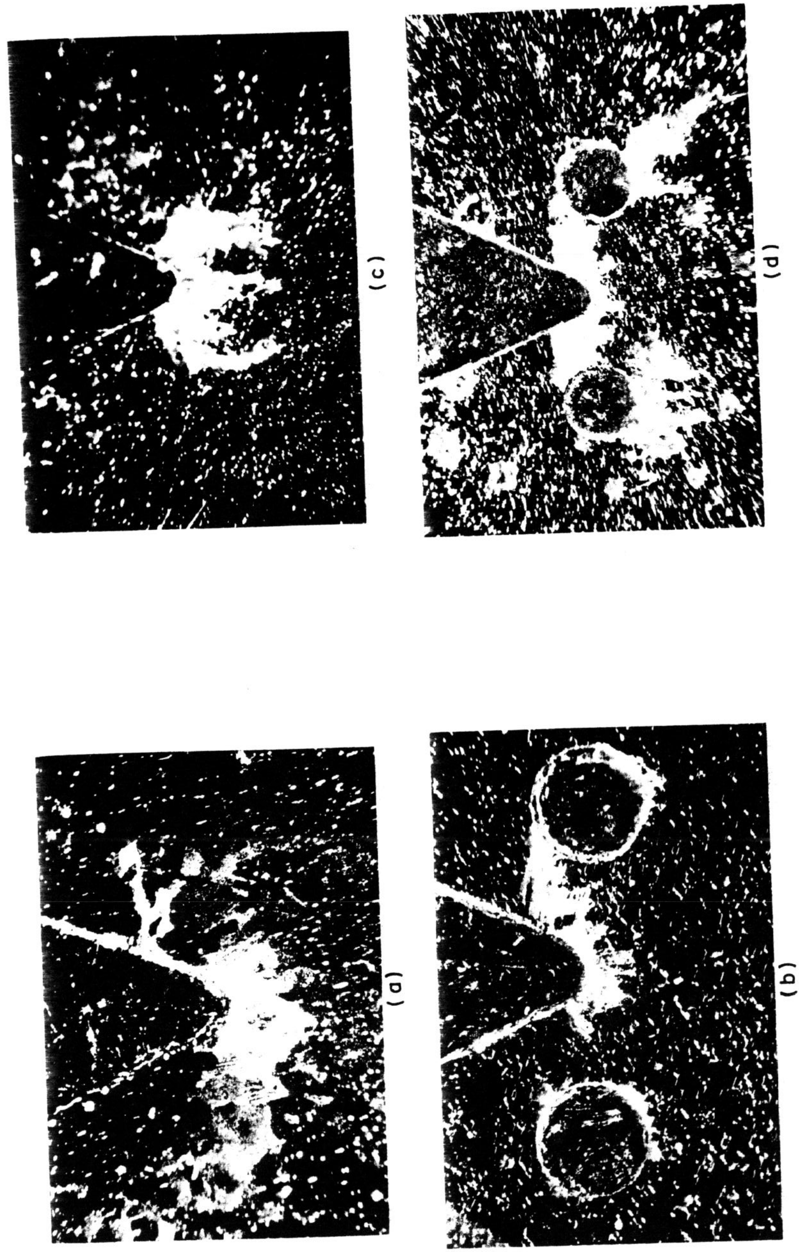


Figure 10. Comparison of the yield zones of standard and drilled samples (R = 0.0448"; θ = 75°) after loading in four point bending to various fractions of the respective general yield loads.
(a) $\sigma/\sigma_{GY}$ = 0.50 standard sample; magnification: 20x
(b) $\sigma/\sigma_{GY}$ = 0.50 two drilled holes; magnification: 20x
(c) $\sigma/\sigma_{GY}$ = 0.715 standard sample; magnification: 14x
(d) $\sigma/\sigma_{GY}$ = 0.715 two drilled holes; magnification: 14x

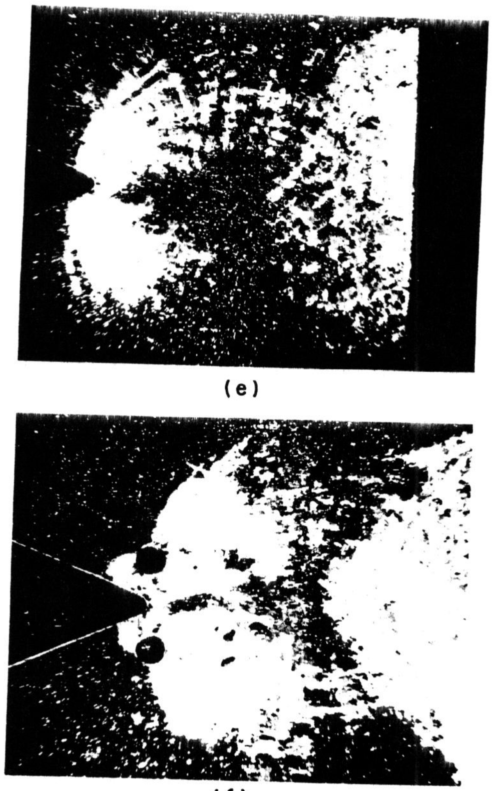


Figure 10.

(e) $\sigma/\sigma_{GY} = 0.98$ standard sample; magnification: 4.6x
(f) $\sigma/\sigma_{GY} = 0.98$ two drilled holes; magnification: 4.6x

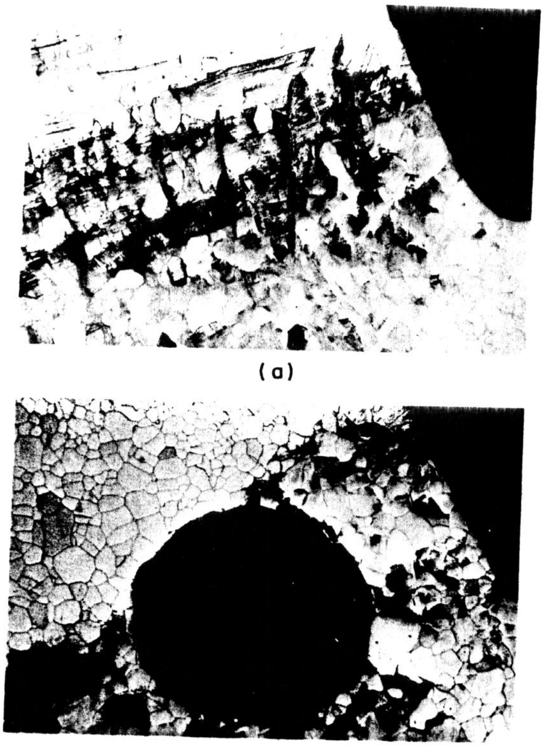


Figure 11. Comparison of the regions of maximum strain [beyond the resolution of etch pitting, see text] with and without two drilled holes ($\theta = 75^\circ$; R = 0.0448") after loading in four point bending to $\sigma/\sigma_{GY} = 0.98$.
(a) Strain concentration $\epsilon > 10\%$ between the hole and the notch side. Magnification: 36x
(b) Maximum strain at the notch side $\epsilon < 10\%$ still resolvable by etch pitting. Magnification: 36x





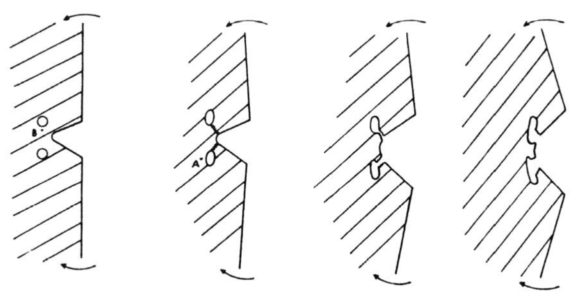


Figure 12. Schematic representation of the fracture mechanism in the presence of two holes at temperatures above the ductile-brittle transition of the drilled samples.

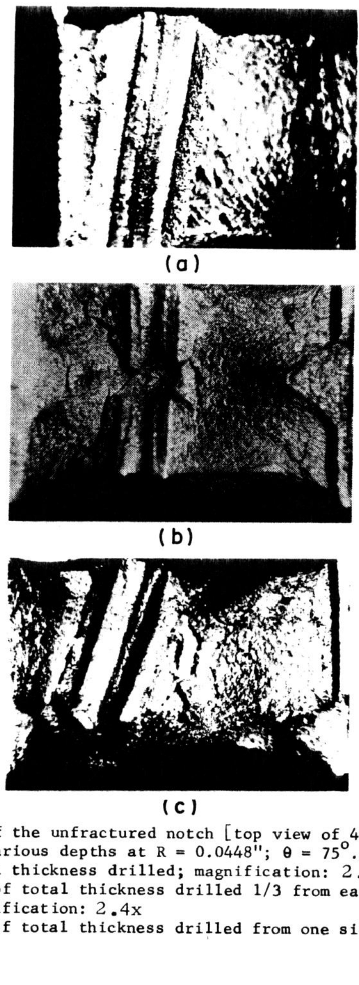


Figure 13. Comparison of the unfractured notch [top view of 4a] for samples drilled to various depths at R = 0.0448"; $\theta = 75^\circ$.
(a) total thickness drilled; magnification: 2.4x
(b) 2/3 of total thickness drilled 1/3 from each side; magnification: 2.4x
(c) 2/3 of total thickness drilled from one side; magnification: 2.4x