IMPACT AND FRACTURE TOUGHNESS PROPERTIES OF MILD AND HIGH TENSILE STEELS

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Abstract

A tentative unifying relationship is obtained to describe the fracture properties of different steel types. The variation of apparent toughness energy required for fracture is compared with that measured from direct impact test. Fracture of low and high strength specimens depend on the crack wave propagation and initiation near to the notch root.

Charpy impact test is carried out under different straining rates at constant notch radius. Therefore the corresponding plane strain fracture test ASTM having same notch radius will depend on the strain rate of the impacted specimen. In case of high tensile Charpy impact evaluation has been found the same as that of the apparent toughness K_A regardless of the impact strain rate, while there is a difference in case of mild steel.

Keywords: Notch field stress, strain rate, critical impact velocity.

Introduction

Fracture toughness evaluation of materials by impact testing has been very common because it attempts to simulate the most severe load and material condition to which a material can be subjected in actual life. However, despite their practical interest, a full understanding of impact test results has to be interpreted. This arises from the notch constraint effect on the apparent fracture toughness of the materials K_A and impact wave velocity on Charpy impact energy. To provide agreement between plane strain fracture toughness and charpy impact results, the impacted specimen were precracked (1) in the same way as the plane strain specimen. Moreover the velocity of impact was controlled to produce the equivalent strain rate. The other constraint of notch properties was considered as constant. Fortunately some agreement has been found between the two models. Introducing the notch constrain effect will yield better agreement (2). It was found that square root of the notch radius is linearly dependant on the material toughness energy whether from impact or from fracture test. Moreover the agreement of fracture test results was noticed on certain specimens having notch radius greater than some critical values, below which the measured value of K_A is constant and equal to K_{iC}. Slow bend specimens ASTM E 399-74 in this paper is used to resemble Charpy notch impact test ASTM 323. Both effects of straining rate and notch property are concluded in this analysis to provide a unifying toughness relationship for mild and high strength steels.

Theoretical Background:

a) Impact notch field state of stress,
Since cleavage of the fractured impacted specimen usually extend to very limited plastic

zone represented by $\kappa\ l \geq d$ from the notch root where,

κ factor
l crack length
d grain diameter

also

$$\sigma_x = \frac{\sigma_n}{\sqrt{2k}} \qquad (1)$$

$$\sigma_y = \frac{\sigma_n}{\sqrt{2k}}(1 - \sqrt{2k}) \qquad (2)$$

$$\sigma_n = V\ \sqrt{E\rho/g} \qquad (3)$$

This behaviour is demostrated in Fig 1

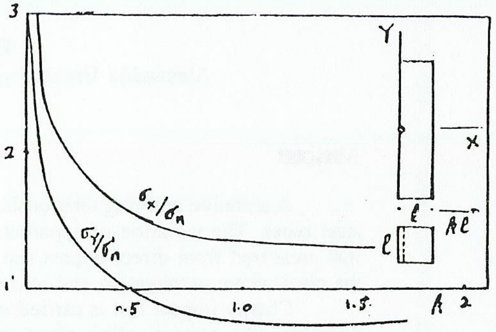


Fig 1

V = hammer velocity = $2\sqrt{gh}$ at commencing of cleavage

At fracture $V = V_{cr}$

$$V_{cr} = \int_0^{e_{max}} \sqrt{\frac{df/de}{\rho/g}}\,de \qquad (4)$$

where $f = ke^n$ (5)

represents the material stress-strain relationship in which f, e are fracture stress and strain respectively. K, n are material constants depending on straining rate as shown in Fig 2

$$V_{cr} = \sqrt{\frac{kng}{\rho}}\ e^{(n+1)/2}\ .\ 2/(n+1) \qquad (6)$$

The critical impact stress $\sigma_{cr} = \sqrt{E\rho/g}\ \ V_{cr}$ (7)

From equation 3,4 the impact momentum will be

P impact dt = (mass) V

V = speed of particles affected by impact, A material Sectional area
m = mass of particles affected by impact, ρ material specific density

$$\sigma_n\ A\ dt = \rho/g\ A\ L/n\ V$$

$$\sqrt{E\rho/g}\ \ AV_{cr}\ dt = \rho/g\ A\ L/n\ V$$

L/n length of specimen affected by impact during time dt
L,W length and breadth of test piece

$$dt = \sqrt{E\rho/g}\ .\ L/n\ V/V_{cr} \qquad (8)$$

substituting $\sigma_{cr} = e\ E_s$ into equation 7, introducing e as critical strain and therefore

$$eE_s = \sqrt{E\rho/g.}\ \ V_{cr}$$

where E_s the secant modulus at critical stress (stress-strain ratio), therefore,

$$e = \frac{1}{E_s}\sqrt{\frac{\rho E}{g}}\ \ V_{cr} \qquad (9)$$

and strain rate will be.

$$\therefore \dot{e} = \frac{e}{dt} = \frac{1}{E_s}\sqrt{\frac{\rho E}{g}}\left(\frac{V_{cr}}{V}\right) n\,L\,\frac{\sqrt{gE}}{\rho} \qquad (10)$$

substituting $n/L = \dfrac{W}{L^2}$

$$\dot{e} = \frac{E}{E_s}(V_{cr})^2/V\ \ \ W/L^2$$

V_{cr} = F (V) in case of brittle fracture, $\frac{E}{E_s} \simeq 2$ at cleavage stress in case of brittle fracture,

$V_{cr} = \sqrt{3}\ V$ at stiffness expressed as, $E = 2\ E_s$

$$\dot{e} = 2(\sqrt{3}\,V)^2/V \quad (w/L^2)$$

$$\dot{e} = 6\ V/W\ (W/L)^2 \tag{11}$$

The strain rate effect on the impact toughness was discerned in (3) and represented by a logarithmic equation reproduced experimentally as

$$k_{cr} = C\ \dot{e} \tag{12}$$

b) Slow bend fracture test evaluation:

Combining notch radius r with critical fracture stress σ_f, a unified relationship between apparent toughness K_A and plan strain fracture toughness K_{IC} is obtained

$$\frac{K_A}{K_{IC}}\{1 + (r + a)^{1/2}\} = 1 + \alpha\,(r/a)^{\frac{1}{2}}$$

where,

$K_A = \sigma_f\ \sqrt{\pi\,a}$

$\alpha = \sigma_u\ \sqrt{\pi\,a/K_{IC}}$

a = notch depth

σ_u = ultimate stress in bending

σ_f = critical fracture stress

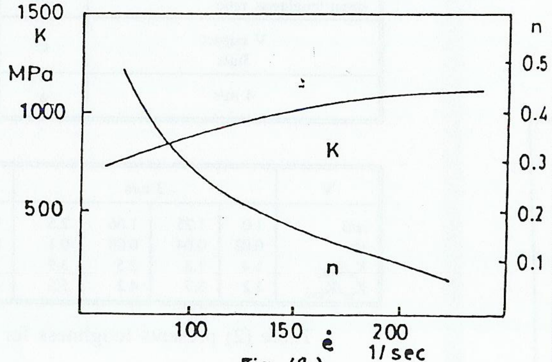


Fig (2)

Retchi and others 1976 has modified the aforementioned expression as

$$\frac{K_A}{K_{IC}}\{1 + (r + a)^{1/2}\} = \alpha\,(r/a)^{\frac{1}{2}} \tag{13}$$

where $\alpha = \dfrac{1 + (r_o/a)^{\frac{1}{2}}}{(r_o/a)^{\frac{1}{2}}}$

where r_o is the critical notch radius that makes $K_A = K_{IC}$

Rethie (4) has found a similar relation of impact energy toughness K_{cv} obtained from charpy test with that obtained from the same test conducted on fatigue precracked specimen K_{cvo} as follow,

$$\frac{K_{cv}}{K_{cvo}}\{1 + (r + a)^{1/2}\} = \beta\,(r/a)^{\frac{1}{2}} \tag{14}$$

where $\beta = \dfrac{1 + (r_c/a)^{\frac{1}{2}}}{(r_c/a)^{\frac{1}{2}}}$

where r_c is the smallest notch radius that makes $K_{cv} = K_{cvo}$ from equations 13,14

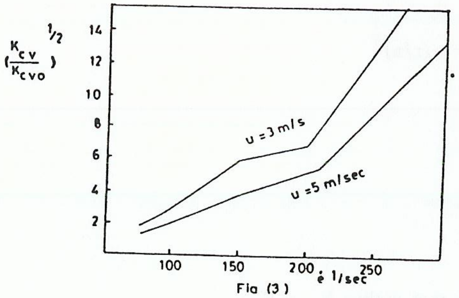
$$\frac{K_A}{K_{IC}} = \frac{\alpha}{\beta}\,\frac{K_{cv}}{K_{cvo}}$$

c) The strain rate impact toughness relationship: In case of mild steel having grain size d from 10 μm to 30 μm the following experimental findings are reported,

$$K_{cv} = C\ \dot{e}^{1.4}$$

$$K_{cvo} = C\ \dot{e}^{1.25} \qquad \text{then} \quad \frac{K_{cv}}{K_{cvo}} = e^{0.15} \tag{15}$$

while for high tensile steel having grain size 220 μm to 300 μm the previous relationship becomes



Fla (3)

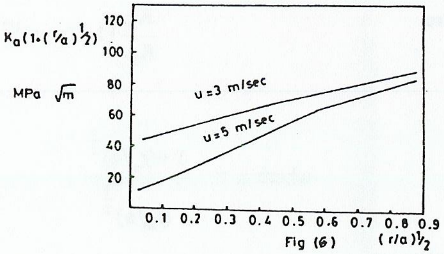
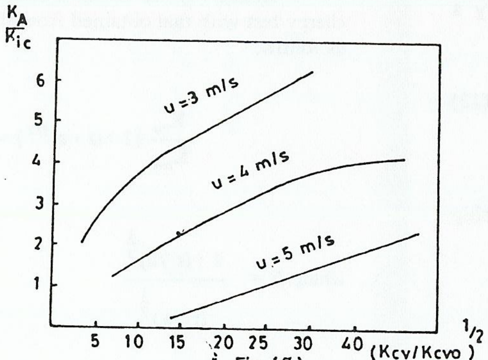


Fig (6)



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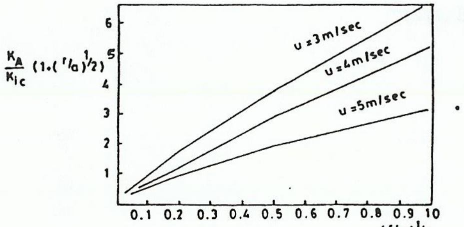

Fig (4)

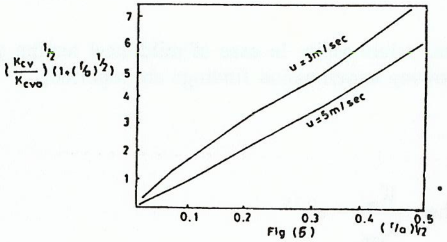

Fig (5)

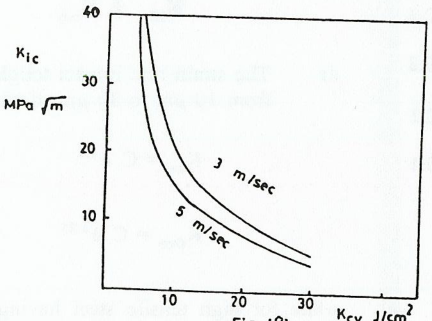

Fig (8)

$$K_{cv} = C\,\dot{e}^{1.32}$$

$$K_{cvo} = C\,\dot{e}^{1.22} \qquad \text{then } \frac{K_{cv}}{K_{cvo}} = e^{0.11} \tag{16}$$

Therefore:

$$\frac{K_A}{K_{IC}} = \frac{\alpha}{\beta}\,\dot{e}^{0.075} \qquad \text{for low strength steel, grain size } d = 30\ \mu m$$

$$= \frac{\alpha}{\beta}\,\dot{e}^{0.055} \qquad \text{for high strength steel, grain size } d = 250\ \mu m$$

At the critical notch radius r_o where $K_A = K_{IC}$

$$\frac{\beta}{\alpha} = \dot{e}^{0.075} \quad \text{or} \quad \dot{e}^{0.055}$$

Given that $\alpha = 1.3\ \beta$ to $2.5\ \beta$ for low strength

and $\alpha = 1.2\ \beta$ to $1.3\ \beta$ for high strength

For a certain specimen dimension ASTM impact given that at certian Hammer velocity of impact then critical speed of impacted particles V_{cr} can be calculated according to the strain rate obtained as given in table (1) as the strain-rate relation of the material as given in equation (11)

Table 1.

strain toughness ratio	α/β	1	1.3	1.4	1.5
V impact 3m/s	$\dot{e}$	88	127	219	370
4 m/s	$\dot{e}$	140	312	520	780

Table 2.

V	3 m/s				4 m/s				5 m/c			
α/β	1.0	1.25	1.66	2.5	1	1.4	2.0	3.33	1.25	1.66	2.5	5.0
r/a	0.02	0.04	0.08	0.1	0.03	0.05	0.1	0.2	0.05	0.1	0.2	0.4
K_a/K_{IC}	1.4	1.8	2.5	3.9	1.45	2.2	3.2	5.5	1.90	2.8	3.25	4.4
K_{cv}/K_{cvo}	1.2	3.7	4.2	5.5	4.5	6.7	12.5	12.5	7.2	11.5	15.1	27.5

Table (2) presents toughness for different notch acuity at various speed of impact.

Results

The variation of impact toughness K_{cv} as a function of strain rate $\dot{e}$ for mild steel is shown in fig (3). The impact toughness is strictly dependant on the critical velocity of impacted particle material of the strain wave velocity. The speed of particle separation is depending on the hammer velocity of impact. The degree of strain rate effect on impact toughness is influenced by the vaiation of material constants k,n during wave of particle separation. The linear dependance of material fracture toughness is confirmed by many others with the square roote of the notch radius. The strain rate effect is indicated in plotting of fracture and impact toughness. The different slopes of these relationship is dependant on hammer speed of impact keeping a linear correlation as long as the grain size of material particles are kept similar as shown in fig (4,5,6).

We observe also that when K_{IC} increases at r = 0,25 mm facture toughnesses K_{cvo}, K_{cv} decrease and decease more rapidly in case of higher impact velocities.

Conclusion

The strong strain rate dependance of the impact toughness of steel materials is depicted. Failure mechanism is proposed to account for impact strain rate rather than the type of steel material represented by factor n and k. It may be noticed also that K_A/ K_{IC} or (K_{cv}/K_{cvo}) are linear functions with r/a regardless of the type the material or its straining rate. Also for both steel types when K_{IC} increases, K_{cvo} and K_{cv} decrease regardless of straine rate or notch radius which r is considered as 0 or 0.25 mm at impact velosities 3 or 5 mt/sec, (fig 7,8).

For other material n,k, constants notch radius and impact velocity results must be reconfirmed particularly when a sudden transition from ductile to brittle mode of failure is expected.

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