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EFFECT OF MICROSTRUCTURE AND NOTCHES ON THE FRACTURE TOUGHNESS OF MEDIUM CARBON STEEL

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Abstract

Fracture toughness (K_{1C}) of medium carbon steel (0.5% C) has been determined by round notched tensile specimen. Two notch diameters (5.6mm and 4.2mm) and three notch angles (α) namely 45^0, 60^0 and 75^0 have been used to observe the effect of notch diameters and notch angle on fracture toughness of the steel. By heat treatment the microstructure of the steel is also varied and its effect on the fracture toughness is also observed. It has been found that fine grained structure improves fracture toughness. Lower notch diameter and higher notch angle show higher value of K_{1C}.

Keyword: Fracture toughness, microstructure, notch, heat treatment

1. Introduction

Medium carbon steels find wide applications in the manufacturing of low cost gears, axles, shafts, fasteners and other similar components (Rollason, 1973, Callister, 1997). These components should have high strength together with adequate toughness to give resistance to crack propagation. The measure of resistance to crack propagation is termed as fracture toughness (Dieter, 1988). In general machine components and structural components are designed over sized in order to avoid failure. This leads to consumption of more material and over weight problem. Hence such efforts are not cost effective. This problem is basically due to non availability of fracture toughness data to the design engineers. In view of this fracture toughness data are very useful in designing machine and structural components which are safe but not over sized and over weight.

Fracture toughness is measured in terms of K_{1C} (plane-strain fracture toughness) where K stands for stress intensity factor at the crack tip, I- denotes that the fracture toughness test is performed in tensile mode and C- denotes that the value of K is critical. When K attains critical value then crack propagation becomes unstable and results in fracture of the components. K_{1C} is a basic material property like yield strength. For low strength and high ductility materials like low carbon steels which find wide applications in the making of pipes for nuclear power plants (Knott, 1979), J_{IC} (J-integral) is determined in stead of K_{1C} due to heavy amount of plastic deformation at the crack tip [3]. In such cases K_{1C} is not a valid data (Dieter, 1988, Wei et al, 1982).

K_{1C} is normally determined by using compact-tension (CT) specimen or single edge notch bend (SENB) or three-point loaded bend specimens which are standardized by ASTM (Dieter, 1988). In these techniques, specimen preparations and test are quite tedious and time consuming. K_{1C} determination by round notched tensile specimen (Fig.1) is quick and tensometer can be used instead of universal testing machine (UTM). It can also be used in preliminary selection of fracture tough materials from a vast lot. Another advantage of such specimen is their radial symmetry, which makes them particularly suitable for studying the impact of the microstructure on fracture toughness of metals. Namely, due to the radial symmetry of heat transfer, the formation of a microstructure along the circumferential area is completely uniform. Further, this method also has significance in measuring the fracture toughness of hard and brittle alloys, since their high notch sensitivity does not allow the creation of a fine crack in the CT or SENB specimen by fatigue or makes it extremely difficult.

2. Theoretical

The expression used for determining K_{1C} from round notched tensile specimen (Dieter, 1988) is given below:

$$K_{IC} = P_f / (D)^{3/2}\ [1.72(D/d) - 1.27] \qquad (1)$$

Where, P_f is the fracture load, D is the diameter of the specimen, and d is the diameter of the notched section (Fig.1). The assumption taken while formulating above expression is that the specimen retains its elastic behavior until fracture occurs. This relation is valid for the D/d ratio between 1.00 and 1.25.

The required plain strain state is, even in the case of a round-notched tensile specimen, created only if the diameter of such specimen is above a certain minimum**.** Wei et al**.** (1982) proved that for round notched and pre-cracked tensile specimens the following condition is to be fulfilled:

$$D \geq (K_{1C}/ \sigma_{ys})^2 \tag{2}$$

Where, σ_{ys} is the yield stress. An additional requirement is that the length of specimen L be at least 4D.

Li and Bakker (1997) evaluated the fracture toughness of a rapidly solidified Al alloy by means of a non-standard procedure. The cylindrical bar specimen used is characterized by a circumferential notch which is fatigue pre-cracked under a rotary-bending load. It was established that the measured values of the critical J-integral for crack initiation and the resistance to stable crack growth can satisfactorily account for the plastic constraint and material state. The work of Bayram et al (1999) in determining K_{1C} by round notched tensile specimen of dual phase steel is significant in this direction. Their work concludes that a fine morphology of ferrite and martensite ensures high K_{1C}. However, there is no data available on K_{1C} for medium carbon steel which is widely used engineering material as mentioned above.

In view of this in the present work a systematic study has been made to determine K_{1C} for medium carbon steel by round notched tensile specimen. K_{1C} has been determined for three notch angles (α) namely 45^0, 60^0 and 75^0 to observe the effect of notch angle on fracture toughness. Two inner diameters (d) of the notches are selected to observe the effect of changing the inner diameters of the specimens on fracture toughness. The Microstructure of the steel is changed by heat treatment and its effect on K_{1C} has been determined.

3. Experimental

3.1 Material

Medium carbon steel rod whose composition is given in Table-I below is used in the present investigation. The diameter of the rod is 10mm.

Table-I: Chemical composition of steel used, wt %.

C	Mn	Si	S	P
0.5	**0.6**	**0.1**	**0.03**	**0.03**

3.2 Specimen preparation

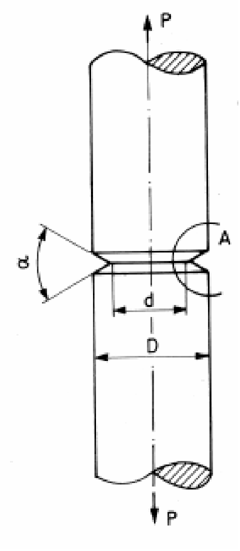
Specimens without notch and with notch have been prepared for tensile test. Cylindrical tensile specimens without notch having diameter 5mm and gauge length 25mm have been prepared as per ASTM standard.
Specimen with notch is shown schematically in Fig.1. Specimens have been prepared as per the ASTM specifications with following dimensions:

Specimen diameter (D):	7mm
Gauge length (L_o):	28mm
Inner diameter of notch (d):	5.6mm and 4.2 mm (two inner diameter notches have been used).
Notch angle (α):	45^0, 60^0 and 75^0 (three notch angles have been used)

3.3 Heat Treatment

Half of the tensometer samples (with and without notch) are given annealing heat treatment and the other half (with and without notch) is used in as-received condition. Initially some samples with or without notches are given normalizing heat treatment and tensile test has been carried out. Since tensile test exhibited very low ductility, so normalizing heat treat is dropped from the present study. Annealing heat treatment consists of heating the samples up to 900°C for half an hour followed by furnace cooling i.e. furnace is switched off and samples are allowed to cool inside the furnace.

After heat treatment samples have been cleaned by emery paper before tensile test.



D = total dia.
d = notch dia.
α = notch angles

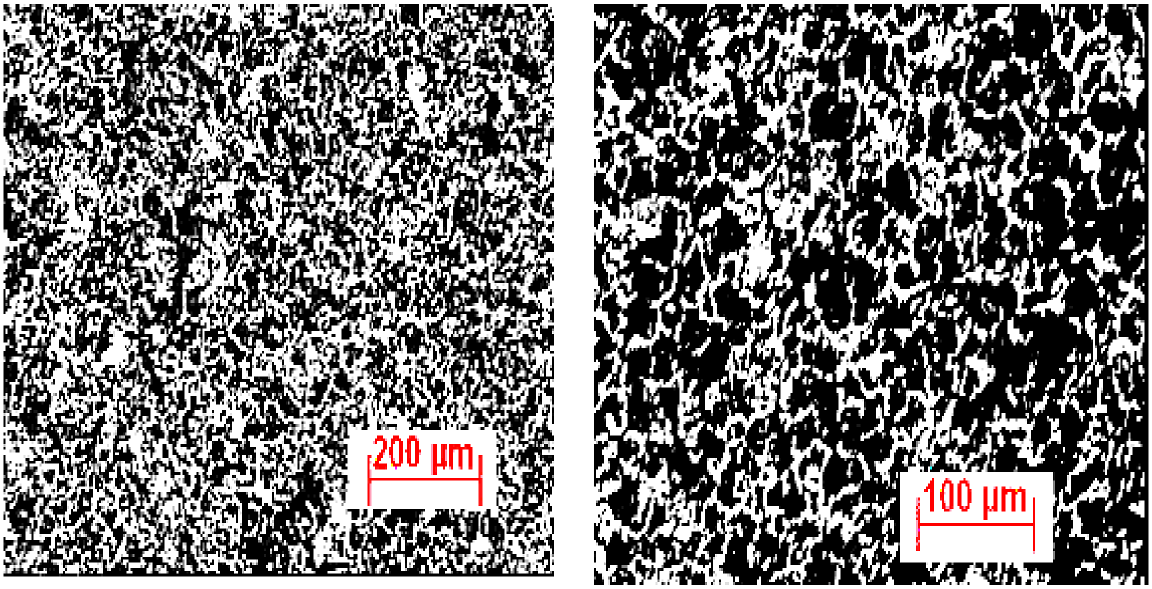
Fig.1: Schematic representation of round notched tensile specimen

3.4 Tensile Test

All the tensile tests have been carried out on Hounsfield tensometer. A cross-head speed of 1mm/minute is maintained throughout the tensile tests. Stress vs strain curves have been recorded on computer which is interfaced with tensometer.

3.5 Metallography

All the steel samples have been prepared for optical microscopy using standard metallographic practice. 2% nital is used as etchant. Volume fraction of pearlite is measured by point counting method and grain size is measured by intercept method.



(a) **(b)**

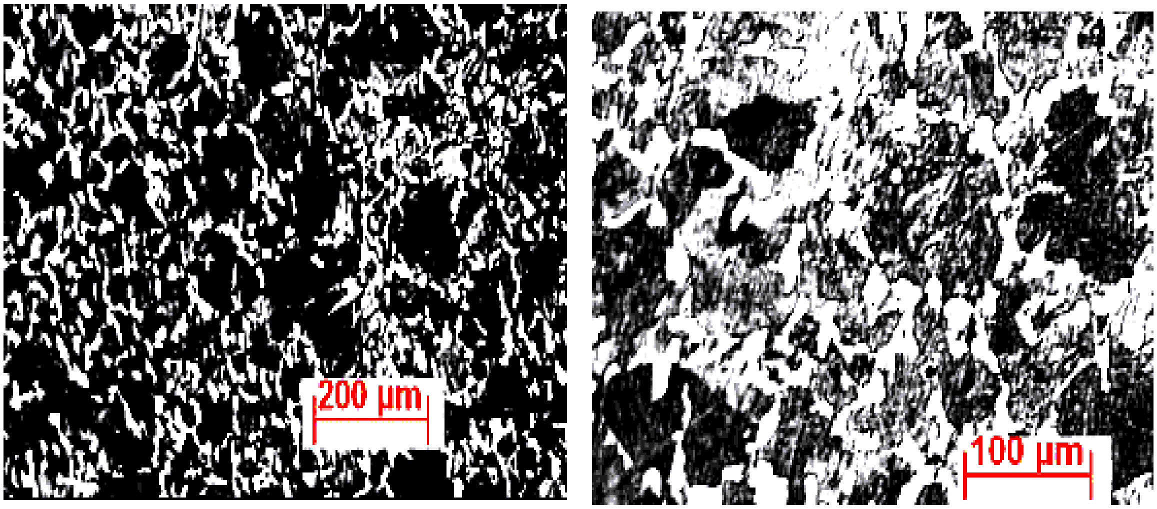
Fig. 2: Microstructure of as-received steel (a) at 100x and (b) at 200x.

4. Results

4.1 Microstructures

Optical micrographs of as-received steel sample at magnification 100X and 200X are shown in Figs.2 a-b respectively. Here black region depicts pearlite and white region depicts proeutectoid ferrite. The average grain size is 17μm.

Optical micrographs of annealed steel sample at magnification 100X and 200X are shown in Figs.3 a-b respectively. Here black region also depicts pearlite and white region depicts proeutectoid ferrite. In annealed structure, pearlite colonies and proeutectoid ferrite are coarser than as-received structure. The average grain size has increased to 42μm. The volume fraction of pearlite estimated by point counting method is found to be 55%.



(a) **(b)**

Fig. 3: Microstructure of annealed Steel (a) at 100x and (b) at 200x.

4.2 Hardness and tensile properties

The hardness, yield strength, tensile strength and % total elongation of unnotched samples of as-received and annealed steels are shown in Table-I below. Each result is an average of three samples.

Table-I: Mechanical properties of unnotched as-received and annealed steels.

Properties	As-received	Annealed
Hardness, VHN	**242**	**215**
Yield Strength, MPa	**471**	**352**
Ultimate tensile Strength, MPa	**759**	**696**
Total Elongation,%	**22**	**27**

It can be observed that hardness, yield strength and ultimate tensile strength of as-received steel decrease as it is annealed but % total elongation (ductility) increases.

Yield stress and fracture stress of notched tensile samples have been determined from load-elongation curve which is obtained from the tensometer interfaced computer. K_{1C} is calculated from Eq. 1 by substituting fracture load, D and d and tabulated in Table-II. It can be observed that yield stress, fracture stress and K_{1C} values are higher for as-received steel as compared to annealed steel (Table-II). For a given notch diameter as notch angle increases, yield stress, fracture stress and K_{1C} increases (Figs.4-5). For a given steel and notch angle, as notch diameter decreases, yield stress and K_{1C} increases (Figs.4-5) but fracture load decreases (Table-II).

Table-II: Yield Stress, Fracture Stress and Fracture Toughness (K_{1C}) of notched as-received and annealed steel samples.

Type of sample	Yield Stress, MPa			Fracture Load, KN			K_{1C} , MPa $m^{1/2}$		
	Notch Angle			Notch Angle			Notch Angle		
	75^0	60^0	45^0	75^0	60^0	45^0	75^0	60^0	45^0
As-Received Notch dia. 5.6mm	**645**	**643**	**610**	**22.93**	**22.83**	**22.72**	**33.5**	**33.3**	**32.7**
Annealed Notch dia. 5.6mm	**500**	**479**	**470**	**20.77**	**20.68**	**19.58**	**30.1**	**29.7**	**28.4**
As-Received Notch dia. 4.2mm	**1035**	**1015**	**997**	**16.96**	**16.54**	**15.88**	**46.3**	**45.1**	**43.4**
Annealed Notch dia. 4.2mm	**987**	**890**	**850**	**14.82**	**13.99**	**12.11**	**40.4**	**37.7**	**32.8**

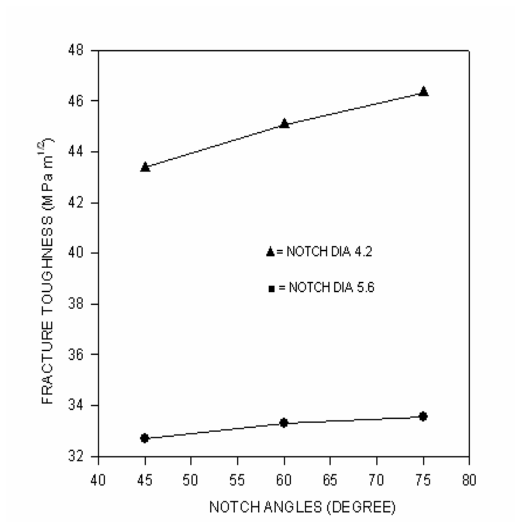


Fig.4: Variation of fracture toughness with notch angle of as-received samples.

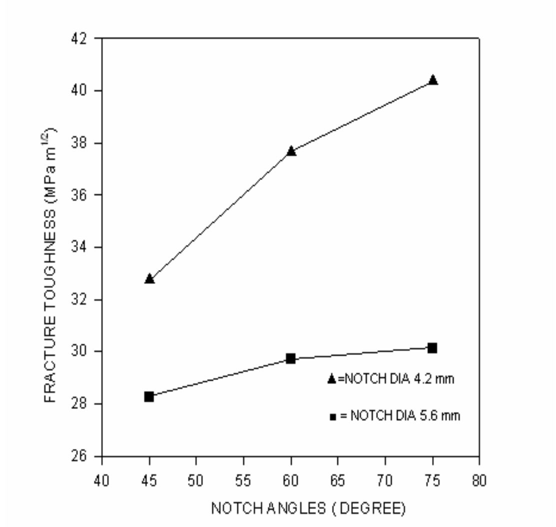
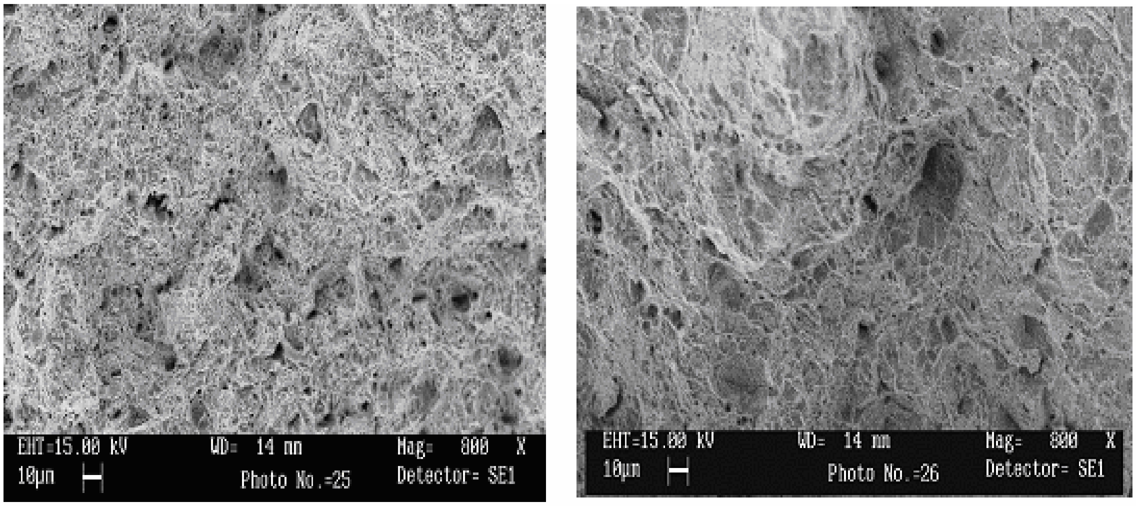


Fig.5: Variation of fracture toughness with notch angle of annealed samples.

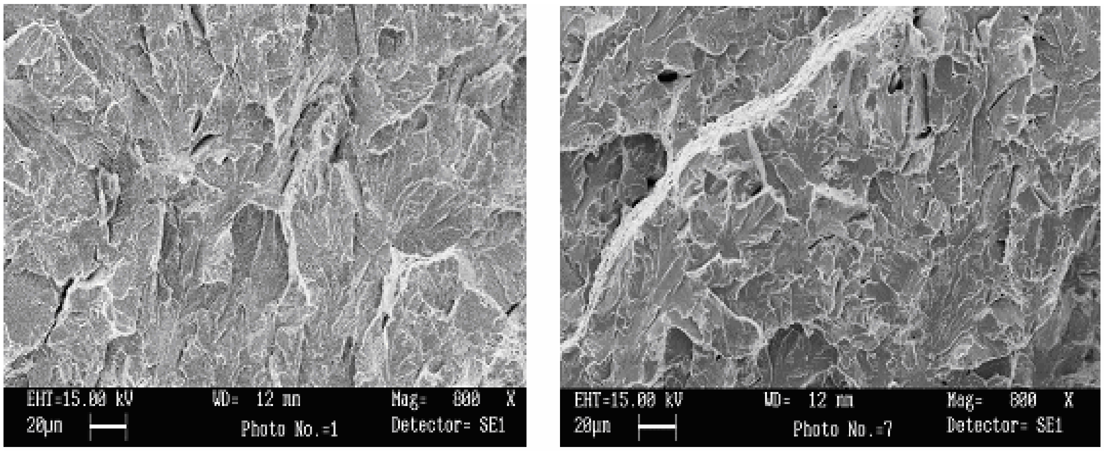


(a) **(b)**

Fig. 6: SEM micrographs of without notch sample of As-received and (b) Annealed sample

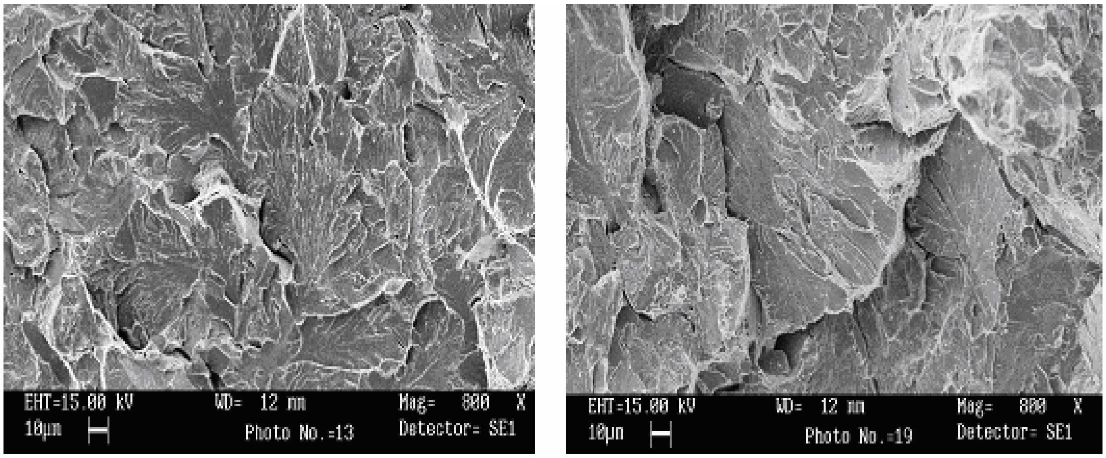
4.3 Fractography

Scanning electron microscope (SEM) fractographs of fractured surface of unnotched tensile samples are shown in Figs.6a-b. Fracture mode is ductile as lots of dimples are visible [1-2]. SEM fractographs of fractured surface of notched tensile samples are shown in Figs.7a-b and Figs.8a-b. Fracture mode is completely brittle as cleavages are visible [1-2].



(a) **(b)**

Fig. 7: SEM micrographs of as-received sample having notch angle 75° (a) Notch depth 5.6 mm (b) Notch depth 4.2 mm.



(a) **(b)**

Fig. 8: SEM micrographs of annealed sample having notch angle 75° (a) Notch depth 5.6 mm and (b)) Notch depth 4.2 mm.

5. Discussion

5.1 Role of microstructure

Microstructure of steel has a strong influence on the fracture toughness (K_{1C}) of medium carbon steel. This has been clearly observed in the present investigation. The fracture toughness of as-received steel sample has been found to be higher than annealed steel sample for the same notch depth and notch angle. For example, K_{1C} value for as-received steel sample (notch depth 4.2mm and notch angle 75^0) is 46.3 MP-$m^{1/2}$ whereas for same notch depth and notch angle, K_{1C} is 40.4 MP-$m^{1/2}$ for annealed steel sample. This difference can be explained on the basis of microstructures of as-received and annealed steel samples. Although both as-received and annealed steel samples consist of proeutectoid ferrite and pearlite (Figs. 2-3). Proeutectoid ferrite is the white region and pearlite is the black region in the microstructure. The presence of pearlite in the samples is confirmed because when it is viewed at higher magnification (1000X), pearlite is resolved into alternate plates of ferrite and cementite [1]. The volume fraction of pearlite (55%) is also the same in both the samples. The parameters which differ are (i) the prior austenite grain size of as-received steel sample (17µm) and annealed steel sample (42µm), (ii) proeutectoid ferrite is finer in as-received steel sample as compared to annealed steel sample (iii) pearlite colony (12µm) is also smaller in as-received steel sample as compared to pearlite colony (35µm) in annealed steel sample and (iv) interlamellar spacing of pearlite. Interlamellar spacing of pearlite measured at 1000X is 0.3µm for as-received steel and 0.9µm for annealed steel sample. These parameters make as-received stronger and harder as compared to annealed steel (Tables-I and II). A fine grained structure gives better resistance to crack propagation (higher K_{1C}) due to higher grain boundary area per unit volume [3]. Grain boundary acts as mild barrier to crack propagation [3]. Pearlite with finer interlamellar spacing is strong than coarser pearlite [1]. Similarly, steel with finer proeutectoid ferrite is stronger than coarser equiaxed proeutectoid in steel as per Hall-Petch relationship [3]. The Hall-Petch relationship states that the smaller the grain size, the higher the strength of the metal. Our observations with respect to microstructure are consistent with the results of Ali Bayram et al [8].

5.2 Role of notch diameter and notch angle

It is observed that introduction of a notch in a tensile sample increases yield strength of the metal irrespective of the heat treatment given to the sample (Table-I and Table-II). This increase can be explained on the basis of introduction of triaxial tensile stresses at the root of the notch [3]. This causes practically zero shear stress at the notch root and hence plastic deformation is completely suppressed. Metal behaves in a brittle manner. It is evident from the SEM fractographs of fractured notched tensile samples (Figs. 7-8). Fracture surface is full of cleavages whereas SEM fractographs of fractured unnotched tensile samples (Figs.6a-b) is of typical ductile fracture having dimples. Our observations with respect to fractography are consistent with the results of Ali Bayram et al [8].

It has been observed that samples with lower notch diameter (4.2mm) shows higher K_{1C} for same notch angle as compared to higher notch diameter (5.6mm) for a given steel (Figs. 4-5). This can be explained on the basis of plastic constraint present at notch root. As plastic constraint decreases (thinner samples), plane-stress condition prevails rather than plane-strain condition (thicker samples). Higher value of K_{1C} is observed. One gets lowest value of K_{1C} of the material when it is tested in plain-strain condition. Then it becomes a material property just like yield stress.

For a given notch diameter as notch angle decreases (sharper notch), it is observed that K_{1C} decreases (Figs. 4-5). With decrease in notch angle, triaxiality of stresses at the notch root increases, plastic deformation is increasingly suppressed. Plain-strain condition approaches and K_{1C} decreases. Our observations on the effect of notch diameter and notch angle on K_{1C} are consistent with the results of Ali Bayram et al [8].

The plane-strain fracture toughness (K_{1C}) of 4340 steel (a medium carbon steel) in quenched and tempered (260^0C) is found to be 50MPa-$m^{1/2}$ from the literature [2]. The reason of slightly higher value of K_{1C} for this steel as compared to the steel used in the present investigation (46.3 MP-$m^{1/2}$ in plane-stress condition) may be due to its higher strength and toughness combination obtained by quenching and tempering heat treatment. The plane-strain fracture toughness (K_{1C}) of a low carbon steel is found to be only 25 MPa-$m^{1/2}$ from the literature [2]. The reason for getting low value K_{1C} is its low strength but high ductility of low carbon steel.

6. Conclusions

1. The microstructure of the steel has a strong influence on the value of K_{1C}. A fine grained structure has been found to have higher value of K_{1C} than a coarse grained structure. For the same volume fraction of proeutectoid ferrite and pearlite, finer morphology of proeutectoid ferrite and finer interlamellar spacing of pearlite ensure higher fracture toughness.

2. Fracture toughness (K_{1C}) of metallic material can be successfully determined by round notched tensile specimen. The value of K_{1C} obtained by round notched tensile specimen is comparable with other methods like compression-tension or three-point bend method.

3. Introduction of notch in a tensile test specimen causes yield strength to increase but ductility (%total elongation) decreases.

4. Introduction of notch in a tensile test specimen causes brittle fracture in spite of the fact that the metal is ductile.

5. It has been observed that samples with lower notch diameter (4.2mm) shows higher K_{1C} for same notch angle as compared to higher notch diameter (5.6mm) for a given steel.

6. For a given notch diameter, as notch angle decreases it is observed that K_{1C} decreases.

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