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THE VISION OF FRACTURE TOUGHNESS ASSESSMENT OF STRUCTURAL MATERIALS FOR QUALITY CONTROL AT THE MANUFACTURING STAGE

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ABSTRACT

Methods to determine fracture toughness of structural materials as documented in ASTM standard E-1820 are neither appropriate for quality control of tonnage materials at the stage of production due to techno-economic reasons nor are suitable for material development owing to their time-consuming nature. This report aims to suggest a common solution to these problems considering measurement of fracture toughness (K_{IVM}) using chevron notched bend bar specimens with either rectangular cross-section (RC) or circular cross-section (CC). The theoretical background for obtaining K_{IVMRC} and K_{IVMCC} and the corresponding normalized stress intensity factors are first discussed in this report. The usefulness of this technique is next illustrated using a number of examples related to the examinations of the (a) effect of inclusions on toughness characteristics of microalloyed steels, (b) optimization of the volume fraction of the constituent phases in dual phase steels, (c) design of heat treatment for cast rolls and (d) designing small specimens for fracture toughness determination.

KEY WORDS

Fracture Toughness, Chevron notched specimen, Microalloyed steel, Dual phase steel, Small specimen

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INTRODUCTION

One of the burning needs for the quality control of structural materials in large scale production is to determine their fracture toughness (FT) in a rapid manner. The standard methods to determine FT of structural materials are well documented in ASTM E1820-01[1]. All the techniques documented in ASTM E1820-01 require test specimens with specific geometric configurations having fatigue pre-cracks. These essential requirements for the standard tests limit rapid determination of FT specifically during the stage of production unlike estimations of hardness, tensile strength, ductility, impact toughness and so on. Consideration of the FT property as one of the quality assurance indices at the stage of production has thus remained a difficult task. One of the possible solutions to this problem could be the development and the subsequent employment of the principle of determining FT (K_{IVM}) of bulk materials using chevron notched specimens. Newmann [2] has reviewed the state of the art in 1990's, whereas Barker [3, 4] has earlier suggested the comprehensive theory for this procedure. The salient procedural details of this technique, as documented in ASTM E1304 [5], is primarily meant for evaluating FT of brittle materials. But its possible applicability in engineering practice specifically for structural steels with FT up to ~100 MPa√m has been indicated earlier [6-10].

Specimens that can be used for determining K_{IVM} using bend bar specimens are either of rectangular (RC) or of circular cross-section (CC). The development of techniques for measuring FT using these specimen configurations, primarily, centers on the estimation of their normalized stress intensity factor (K^*_{IVM}), and analysis of the extent of the stable crack growth. The theoretical background for achieving K_{IVMRC} and K_{IVMCC} which necessarily deals with formulations for K^*_{IVMRC} and K^*_{IVMCC} is first discussed in this report. This is followed by an account of the stability analyses of chevron notches in long bend bar specimens. The usefulness of this technique in material development and in quality control is next illustrated using a number of examples.

THEORETICAL BACKGROUND

Estimation of FT using chevron notched (CVN) specimens requires measurement of specimen dimensions, determination of maximum load during a test and calculation of the minimum normalised stress intensity factor (SIF), $Y^*_{\min} (= K^*_{IVM})$. The required load can be determined rapidly by an experiment, and the magnitude of $Y^*_{\min}$ can be computed in a short time, provided the software amenable to estimate $Y^*_{\min}$ for the CVN configuration of interest is available. The magnitude of $Y^*_{\min}$ can be estimated as follows: The energy release rate for a chevron notched specimen is expressed as [10, 11]:

$$G = (P^2/2)[dC_v(a)/dA] \tag{1}$$

where P is load, C_v is compliance of a chevron notched specimen, a is crack length and ΔA is the area of crack extension. The magnitude of ΔA is $b\Delta a$, where b is the width of a crack at any instance of crack length $a = a_0 + \Delta a$; a_0 is the initial crack length. Using equation (1), suitable relations between the instantaneous crack length and the associated notch geometry, and the relation between energy release rate and

SIF, one can define the dimensionless SIF for chevron notched (Y^*) and straight cracked (Y) specimens [10].

Estimation of K_{IVMRC} : Chevron Notched Rectangular Bend Bar Specimens

The K_{IVMRC} value of rectangular specimens can be expressed as [12]:

$$K_{IVMRC} = \frac{P}{B' W^{1/2}} Y^*_{\min} \tag{2}$$

where B´ and W are the thickness and the width of a specimen, P is the critical load and $Y^*_{\min}$ is the minimum normalized stress intensity factor, and is given by the relation:

$$Y^*_{\min} = \left[\frac{1}{2} \frac{dCv(\alpha)}{d\alpha} \left(\frac{\alpha_1 - \alpha_0}{\alpha - \alpha_0} \right) \right]^{1/2}_{\min} \tag{3}$$

where α, α_0 and α_1 are the normalized depths given by $\alpha = a/W$, $\alpha_0 = a_0/W$, and $\alpha_1 = a_1/W$ respectively as shown in Fig.1 and $Cv(\alpha)$ is the normalized compliance of a test piece. An analytical expression for $Cv(\alpha)$ as a function of specimen geometry has been suggested by Wu Shang-Xian [13] and this is used to estimate the values of Y^* as function of α and consequently $Y^*_{\min}$. Once $Y^*_{\min}$ is computed, evaluation of K_{IVMRC} requires the critical maximum load from experiments apart from the specimen dimension to calculate FT of the specimens.

Estimation of K_{IVMCC} : Chevron Notched Round Bend Bar Specimens

The dimensionless stress intensity factors for chevron notched (Y^*) and straight cracked (Y) round specimens are [10]:

$$Y^* = \frac{K_I}{\left(P/D^{3/2}\right)} = \frac{1}{2}\left[\frac{1}{\tan\theta(\alpha - \alpha_0)} \frac{d(E'C_v D)}{d\alpha} \right]^{1/2} \quad \text{...Chevron notch} \tag{4}$$

$$Y = \frac{K_I}{\left(P/D^{3/2}\right)} = \frac{1}{2}\left[\frac{1}{\alpha^{1/2}(1-\alpha)^{1/2}} \frac{d(E'CD)}{d\alpha} \right]^{1/2} \quad \text{...Straight crack} \tag{5}$$

where D is the diameter of a round bar, θ is the included chevron notch angle, $\alpha_0 = a_0/D$ and $\alpha = a/D$ as described in Fig.2. It is considered that [10]:

$$Y^* = Y\left[\frac{\alpha^{1/2}(1-\alpha)^{1/2}}{\tan\theta(\alpha - \alpha_o)} \right]^{1/2} \tag{6}$$

Equation (6) represents the expression for computing Y^* for CVN round bar specimens.

The normalized stress intensity factor for a K_{IVMCC} specimen with straight crack, has been earlier obtained by Daoud and Cartwright [14] using finite element analyses (FEA), and by Bush [15] using experimental compliance measurements on K_{IVMCC} specimens.

Using the expressions suggested by Daoud et. al. and Bush et. al., Ray and Poddar [14, 15, 10] have shown that the FT of a CVN round bar specimen in three point bend loading can be expressed as:

$$K_{IVMCC} = \frac{P_C}{D^{3/2}}\left(Y^*_{fem}\right)_{\min} \quad \text{or} \quad K_{IVMCC} = \frac{P_C}{D^{3/2}}\left(Y^*_{\exp}\right)_{\min} \tag{7}$$

where $$Y^*_{fem} = 4.51\left(\frac{S}{D}\right)\left[\frac{\alpha^{3/2}(1-\alpha)^{1/2}}{\tan\theta(\alpha-\alpha_o)}\right]^{1/2}\left(1.04 - 3.64\alpha + 16.86\alpha^2 - 32.59\alpha^3 + 28.41\alpha^4\right) \tag{8}$$

$$\mathrm{Y}^*_{\exp} = \frac{S}{D}\left[0.12 + 19.85\alpha - 193.81\alpha^2 + 1170\alpha^3 - 3284\alpha^4 + 3411\alpha^5\right]\left[\frac{\alpha^{1/2}(1-\alpha)^{1/2}}{\tan\theta(\alpha-\alpha_o)}\right]^{1/2} \tag{9}$$

and P_C = critical load to cause fracture.

The above formulations for K_{IVMCC} can be employed to estimate the FT of CVN round bar specimens with the knowledge of the specimen dimensions, loading-span length, the critical load for the fracture and the minimum value of Y^*_{fem} or $Y^*_{\exp}$.

STABILITY OF THE CHEVRON NOTCH IN THREE-POINT BEND SPECIMENS

When a crack initiates from a chevron notch, there is always an over load, which supplies surplus available energy to accelerate the crack after initiation. This overload, in turn, leads to estimation of FT. Therefore, it is necessary that a specimen experiences some stable crack growth before fracture. If the stability of a specimen is sufficiently high, it can resist the accelerated crack and stabilize the crack growth upto some crack extension, Δa. If the stability of the specimen is insufficient, the initial accelerated crack will result in catastrophic fracture. The crack must take some relative crack extension $\Delta\alpha = \Delta a / D$ to transform from accelerated propagation to stable growth. The stable and unstable regions are shown in Fig.3. This is the domain of stability analysis.

Bluhm [16] proposed that stability of CVN specimens can be characterized by the constant load stability factor S_p and the constant displacement stability factor S_δ, which are functions of α, α_0, α_1 and $C_v(\alpha)$. The relative crack extension $\Delta\alpha_C = (\alpha_C - \alpha_O)$ is a parameter which affect the stability of a specimen. Specimens with larger $\Delta\alpha_C$ have a larger capacity to relax in the initial pop-in. Some typical variations of K_{IVMRC} values with the CVN geometry obtained by Wu [17] are shown in Fig.4. Typical plots of critical crack extension ($\Delta\alpha_c$) versus initial crack length (α_0), computed using procedures based on Y^{*}_{fem}, for K_{IVMCC} are shown in Fig.5. The magnitude of α_0 for maximum stable crack extension for K_{IVMRC} specimens are found to be between 0.2 and 0.3. For rectangular specimens Xian [17] has shown this value to be around 0.3, and Calomino [18] has reported this value to be between 0.2 and 0.3. For K_{IVMCC} specimens, these values are found to be 0.18 and 0.08 for the considerations of Y^{*}_{fem} and $Y^{*}_{\exp}$ respectively. Comparison of these results with that of K_{IVMRC} specimens indicate a value of α_0= 0.2 to be rational.

EFFECT OF INCLUSIONS IN FRACTURE TOUGHNESS OF MICROALLOYED STEELS

Severe demand for estimating FT as a function of (a) chemistry, (b) microstructure, and (c) cleanliness exist in the industry particularly for the inspection and quality control of high strength steels. For microalloyed steels having yield strength$\approx$350-450 MPa and with expected FT $\approx$100-150 MPa√m, the thickness required for estimating plane strain fracture toughness (K_{IC}) would be $\approx$120-450 mm. This requirement hinders determination of (K_{IC}) using LEFM approach; while determination of EPFM based toughness criteria are significantly time consuming as to implement the techniques for the quality control of these steels. The applicability of FT measurement using K_{IVMRC} specimens to overcome this industrial problem related to quality control of microalloyed steels is illustrated in this section.

Four Nb-microalloyed semi-killed steels were selected for this investigation; the chemical compositions of the steels are: C: 0.18-0.19, Mn: 1.31-1.54, S: 0.027-0.028, P: 0.017-0.033, Si: 0.06-0.081 and Fe-bal. (all in mass %). The microstructures of the steels in the as-received condition reveal ferrite and pearlite. The average volume fraction of inclusions and the grain size are found to be 0.4% and 11µm, respectively. The average tensile properties of the steels are: yield strength =422-442 MPa, tensile strength=551-584 MPa, and % elongation=21-25. The FT experiments were carried out using R_{IVRB} specimens with cross-section of 18x12 mm having span length of 72 mm and a total length of 130 mm. These tests were carried out using an Instron1344 machine at the temperature of 293K using a cross head speed of 1.67mm/min. The maximum load values used in this test were recorded for subsequent calculation of K_{IVMRC} using equation (2).

The magnitude of K^{*}_{IVRC} was computed using the expression given by Wu Shang-Xian [13] and are found to be in the range 24.68-26.50 Using these values of normalized stress intensity factors, the magnitudes of K_{IVMRC} were estimated and are found to be in the range 94.4-107.7 MPa√m. The closer range of K_{IVMRC} values are in good agreement with the closer compositions of the materials. Interestingly, the FT [19] and the Charpy impact energy (CIE) can be empirically co-related with volume fraction of inclusion as:

$$K_{IC} = [2\sigma_y . E(\pi/6)^{1/3} D]^{1/2} (V_f)^{-1/6} \tag{10}$$

$$CIE = A . D (V_f)^{-1/3} \tag{11}$$

where D is inclusion diameter and V_f is the volume fraction of inclusions. The equation given by Hahn and Rosenfeild [19] indicates that the measured variation in the volume fraction of inclusion can induce and error of ~3%, while the same variation in V_f can induce an error of ~16% in CIE. Thus the evaluated K_{IVMRC} values indicating standard error of <4% are in excellent agreement with the predictions given by empirical relations between K_{IC} and V_f.

EMPLOYMENT OF CHEVRON NOTCH FRACTURE TESTING IN MATERIAL DEVELOPMENT

The development of ferrite-martensite dual phase (FMDP) steels for their excellent combination of strength, ductility, continuous yielding, formability, and high work hardening rate has been primarily exploited by the automotive industry. The volume fraction of martensite (V_M) is usually optimized at 0.25 to achieve suitable combination of ductility and impact toughness. It is demonstrated earlier [20] that improved combination of mechanical properties of dual phase steels can be achieved beyond V_M>0.25 by suitable intercritical quenching treatment (IQT). The application potential of such steels can be judged from the understanding of their variation of fracture and fatigue properties as function of V_M. This section illustrates this aspect using determination of FT by K_{IVMRC}.

A microalloyed steel [C= 0.16, Mn=1.32, S=0.002, P=0.013, Si=0.44, Cr=0.03, Mo=0.09, V=0.056, B=0.002, and N=0.4, Fe= bal., all in mass %.] was subjected to IQT as shown in Fig.6 to generate FMDP steels with V_M between 0.3-0.8. Microstructural examinations were made using quantitative metallography, tensile tests were done following ASTM standards E8-M [21] and K_{IVMRC} values were measured on 12mmx18mmx100mm specimens. The K_{IVMRC} tests were carried out in 3 point–bend loading at room temperature using a crosshead speed of $2x10^{-2}$mm/sec. The magnitudes of K_{IVMRC} were estimated using equation 2. In addition, the dynamic fracture toughness values of fatigue precracked Charpy V-notched specimens were also determined with the help of an instrumented Impact testing machine. The magnitude of K_{ID} and K_{IJD} were estimated using standard expressions.

Typical microstructures of the heat treated FMDP steels are shown in Fig.7 whereas the variations of the microstructural features with varying ICT are shown in Fig.8. The variation of fracture toughness values determined using quasi static and dynamic fracture testing are shown in Fig.9 and Fig.10 [22], respectively.

The variation of K_{IVMRC} with V_M indicates that toughness increases for specimens containing V_M up to 0.6 then decreases with further increase in martensite. The variation K_{IVMRC} with V_M is similar to the reported variation of impact energy with V_M. Interestingly the dynamic fracture toughness of the parameters show insignificant change for specimens containing V_M up to 0.45 followed by sharp increase up to V_M=0.6 and then seemed to achieve a saturation plateau. A comparative assessment of impact energy quasi-static fracture toughness and dynamic fracture toughness indicate the FMDP steels containing 0.5<V_M<0.6 exhibit the best range of toughness. Thus use of K_{IVMRC} specimens for searching the appropriate state of the microstructure to achieve the best possible fracture toughness seems to be the best option for material development or for optimizing heat treatment process. The refined microstructural characteristics of ferrite and martensite without any carbide precipitation in ferrite of these microstructures is the answer. The lower toughness of the specimens with V_M<0.5 is due to relatively coarser ferrite interspread with carbide precipitation while lower toughness for specimens containing V_M>0.6 due to coarser martensite, in agreement with the suggestions given by Kang and Kwon [23].The observed effect is illustrated using fractography and analyses of fracture path.

DESIGN OF HEAT TREATMENT FOR CAST ROLLS

Indefinite chilled double poured (ICDP) cast iron rolls which find significant applications in continuous hot rolling of steel plates and strips, exhibit a gradient microstructure consisting of chilled cast iron (CCI) on the rim and gray iron at the core. The CCI shows high hardness and provides excellent abrasion resistance but is associated with poor FT which leads to micro or macro spalling causing mal-functioning of the rolls. The design of heat treatment of cast iron rolls should thus incorporate tailoring the microstructure to achieve best FT. The rolls contain considerable amount of retained austenite (RA) which can be transformed into martensite by soaking treatment; the time and temperature of soaking are critical parameters for suitable application of ICDP rolls. The heat treatment of ICDP rolls vis-à-vis their FT has been examined in this section.

The experimental work incorporated generating varied microstructures (by soaking at different temperatures between 300-450^{0}C) on samples taken from the rim of a commercial ICDP rolls and subsequently subjecting the samples primarily to microstructural analysis, hardness and fracture toughness measurement; the chemical composition of the roll materials is: C-3.32, Si-0.98, Mn-0.70, P-0.09, S-0.02, Cr-1.8, Ni-4.15, Mo-0.32 and Fe-bal. (all in mass %). In general, the microstructure of CCI exhibits a mixture of ledeburetic carbide and transformed austenite (TA), which, in turn, consists of a mixture of martensite, secondary carbide, and RA. Soaking treatment primarily converts RA to martensite. Quantative metallographic examinations were carried out to estimate the amount of carbide, RA and graphite. The macrohardness of the heat treated samples and the microhardness of cementite and TA were measured. Fracture toughness tests were done on unprecracked single edge notched bend (SENB) and K_{IVMRC} specimens with help of an Instron machine at the room temperature of approximately ~25^{0}C.

The major results of this investigation are summarized as variation of RA, Rockwell hardness and FT estimated by SENB and CVN specimens versus soaking temperature, as shown in Fig.11, 12, and 13 respectively. It is surprising to note that the variation of FT with soaking temperature almost resembles the nature of variation of R_C with soaking temperature. The increase in macrohardness (Fig.12) is expectedly due to the reversion of RA, while the initial decrease in R_C is due to relief of residual stresses and the final decrease is due to increased amount of tempered martensite. The initial increase in fracture toughness is due to the elimination of micro residual stresses, but that between 300 and 425^{0}C is possibly due to the build up of compressive residual stresses owing to the transformation RA to martensite. It is interesting to note that the magnitude of K_{IVMRC} bears an almost a constant ratio with that of K_{ISENB}, but the value of K_{IVMRC} is always higher than the latter. The marginally higher values of K_{IVMRC} compared to that of K_{ISENB} could possibly emerge form the lack of stability analyses for this type of specimens. One can note that the magnitudes of K_{IVMRC} lie in the range 22.3–25.4 MPa√m and that of K_{ISENB} lie in the range 20.8-23.1 MPa√m, in agreement with the earlier reports [24]. The results thus infer that K_{IVMRC} specimens can be used to optimize mechanical properties of the rim of ICDP rolls.

DETERMINATION OF FRACTURE TOUGHNESS USING CHEVRON NOTCHED SMALL SPECIMENS

The development of a large variety of emerging advanced materials has brought forward newer challenges to the technologists for characterization of their mechanical properties specifically in small volumes. The major problems associated with the determination of FT of miniature specimens are: (a) fatigue pre-cracking, and (b) satisfying thickness criterion for determining K_{IC}. Chevron notched miniature specimens can be hypothesized to provide K_{IC} for relatively brittle materials and this feasibility has been explored considering K_{IVMCC} specimens.

The experiments were carried out on two types of pearlitic steel having composition as shown in the parenthesis: (C=0.82%, Mn=0.75%, Si= 0.015%, P= 0.015, Cr= 0.03, Ni= 0.002, Cu=0.03, Al= 0.002, Ca=0.001, Fe= Balance). Specimens were annealed either at 923K for 30 min (type-A) or at 1073K for 60 min (type-B) followed by furnace cooling. The inter-lamellar spacing values of type-A and type-B specimens are found to be 167 and 549 nm respectively. The tensile properties and the hardness values of the steel were as follows: yield strength: σ_{YA} =876 MPa, σ_{YB} =751.5 MPa, tensile strength: σ_{TA} = 965 MPa, σ_{TB} = 846.5 MPa, percentage elongation: e_A= 13.2, e_B= 11.16, hardness: VHN_A20= 289 and, VHN_B20 = 248. The subscripts A and B refer to the two types of microstructures of the steel. The fracture tests were carried out using K_{IVMCC} specimens having 4 mm diameter and 20 mm length with normalized initial notch length of 0.3 and chevron notch angle of 60^0. These tests were done with the help of a Universal 50 kN capacity Shimadzu Testing Machine in three point bend loading at 298K using cross-head velocity of 0.1 mm/min. A typical fabricated miniature specimen is shown in Fig.14.

The estimated FT values of the miniature specimens which typically weighed less than 3 gm are shown as bar diagrams in Fig.15. These results infer that the estimated FT values are repetitive in nature and the extent of stable crack growth is 0.24 in close agreement with the theoretically estimated magnitude of 0.2 for K_{IVMCC} specimen [17, 18]. The average K_{IVMCC} values of the type-A and type-B specimens are found to be 56 and 76 MPa$\sqrt{m}$ respectively and the order is in satisfactory agreement with reported results [25, 26] on larger specimens. Since lower inter-lamellar spacing results in higher K_{IC}, FT of type-A and type-B specimens also bear expected correspondence between FT and microstructure.

CONCLUDING REMARKS

The state of the art of determining fracture toughness of structural materials using bend bar specimens has been presented with several applied examples. An overview indicates that this test procedure is rapid enough to assess fracture toughness of materials and can be employed for the quality control practices or during the development of emerging materials.

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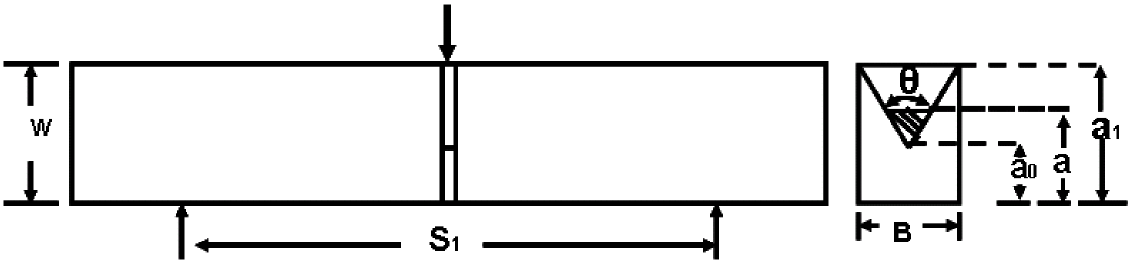

Fig. 1: Geometry of the chevron notched specimen of rectangular cross section under the three point bend (span: S_1) loading configuration.

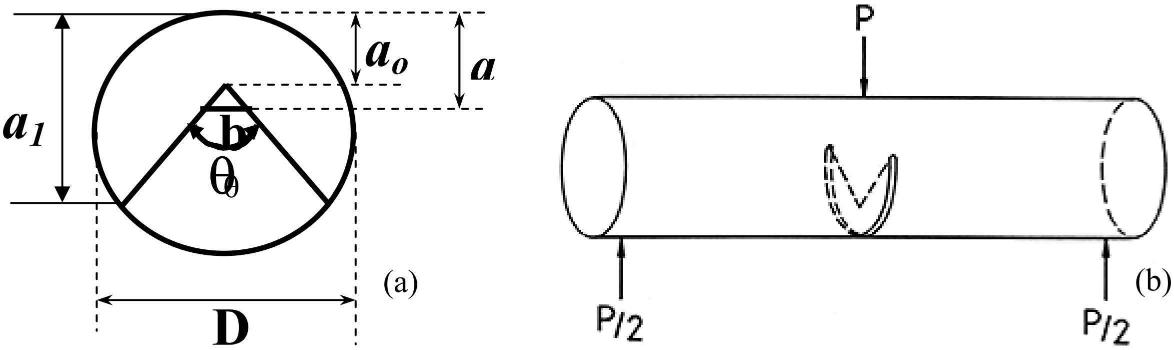

Fig. 2 Schematic diagrams of (a) cross sectional view at the crack plane and, (b) three-point bend loading configuration of chevron notched round bar specimen. The normalized crack dimensions a_o/D, a/D and a_1/D are referred in the text as α_o, α and α_1 respectively.

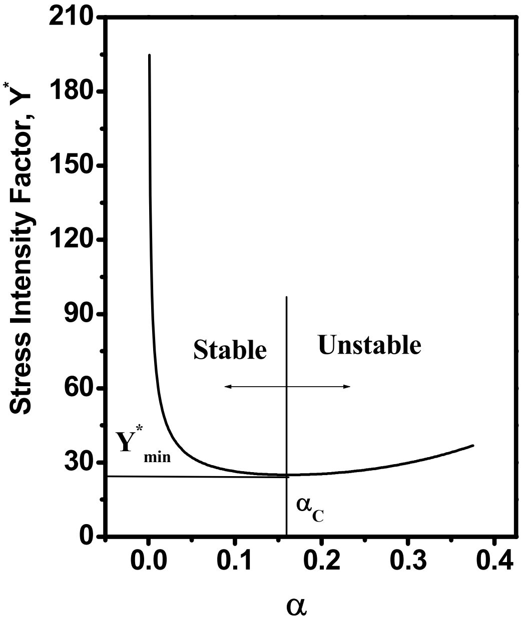

Fig.3 Typical graph showing stable and unstable regions

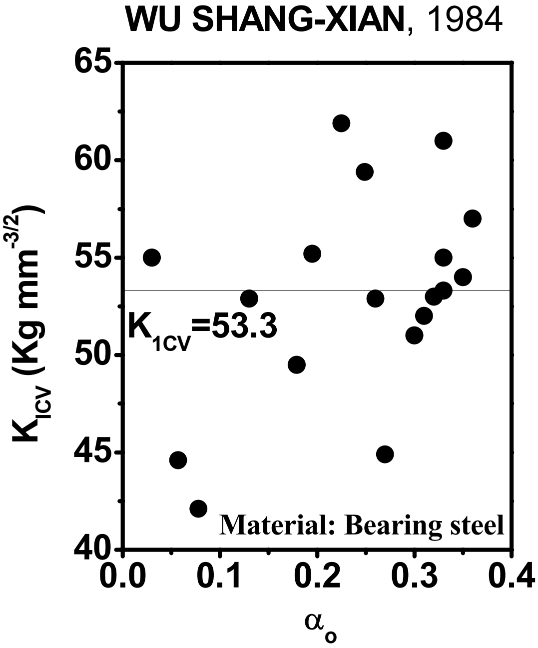

Fig. 4 Variation of quasi static fracture toughness (K_{1VRB}) with initial crack length. α_0.

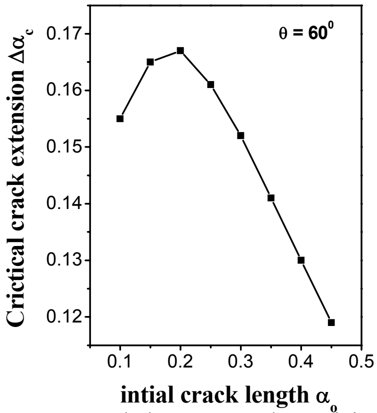

Fig.5 A graph between the critical crack extension and the initial notch lengths

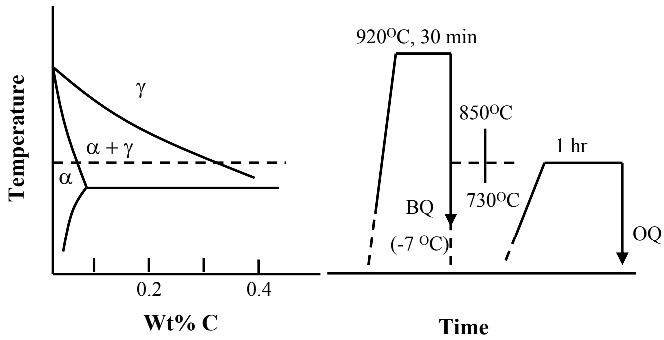

Fig. 6 Typical heat treatment cycle for intercritical quenching treatment

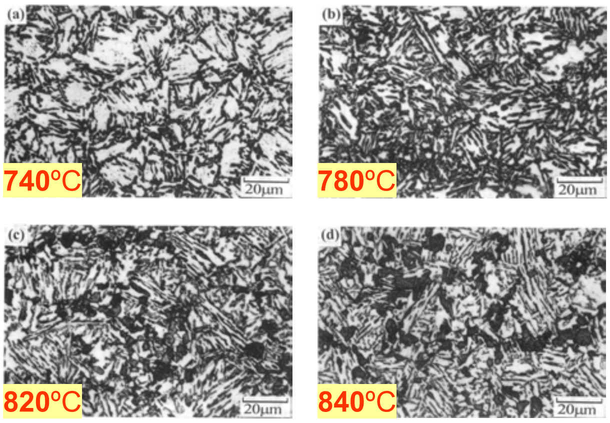

Fig. 7 Typical microstructures of differently heat treated IQT specimens exhibiting ferrite and martensite.

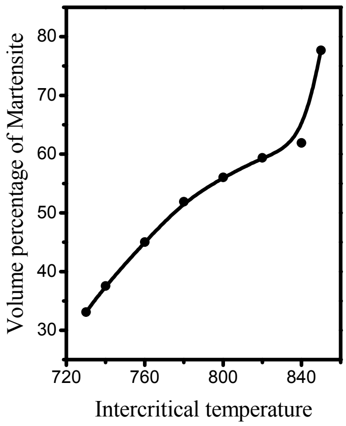

Fig. 8 Influence of intercritical temperature on the volume fraction of martensite.

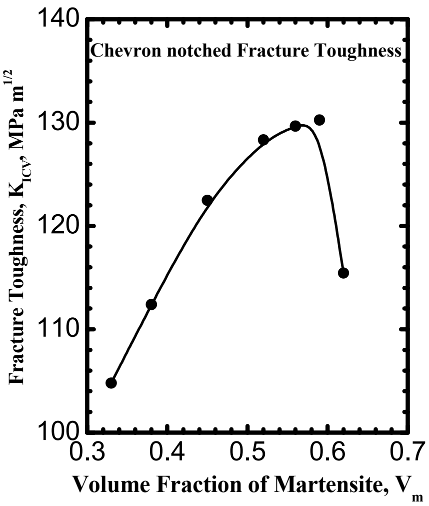

Fig. 9 Variation of quasi static fracture toughness values with volume fraction of martensite.

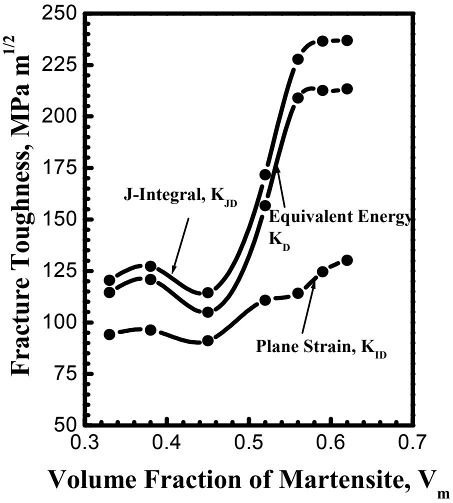

Fig. 10 Variation of dynamic fracture toughness values with volume fraction of martensite.

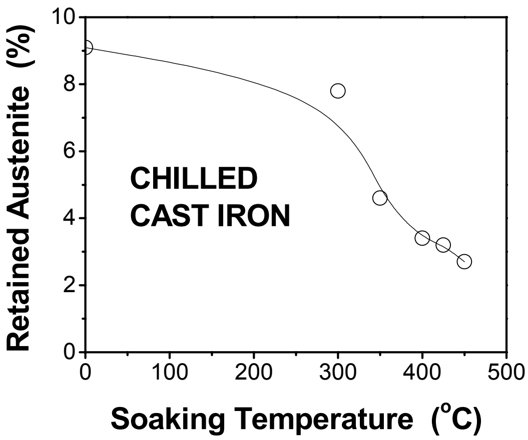

Fig.11 Variation of retained austenite with soaking temperature.

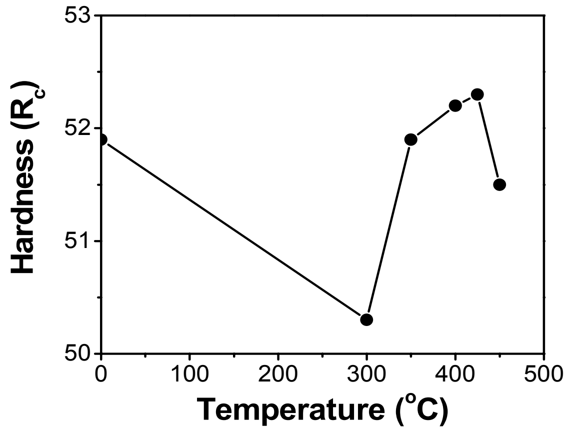

Fig.12 Variation of average macro-hardness with soaking temperature.

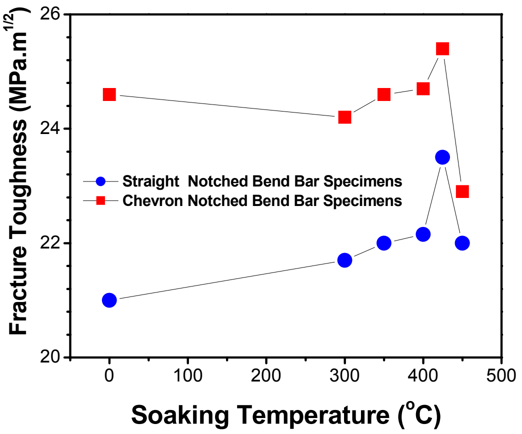

Fig.13 Variation of fracture toughness with soaking temperature.

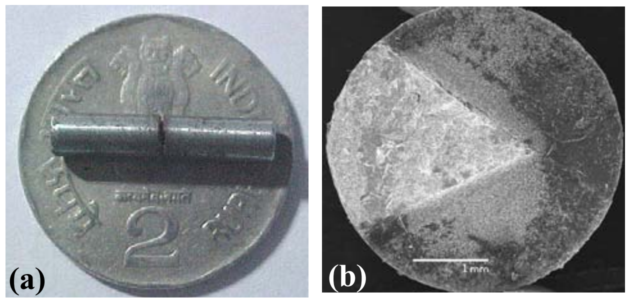

Fig. 14 Typical (a) fabricated miniature specimens on a two rupee Indian coin and (b) fracture surface of a chevron notched round bar miniature specimen.

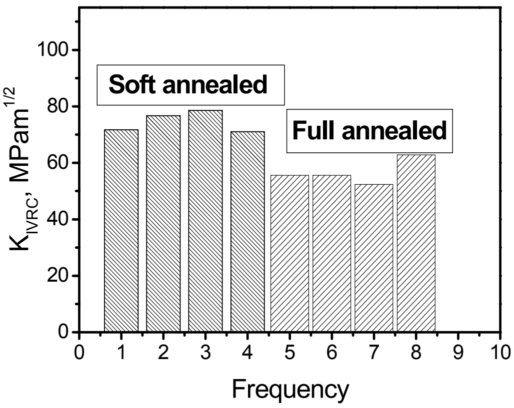

Fig. 15 Estimated fracture toughness values of Type A and Type B specimens.