

Characterization of Fracture Toughness of As-Cast Si-Mo-Cr Ductile Cast Iron

Nanak Ram^{1,*}, Vijay Gautam²

Abstract

In the present study, a Si-Mo-Cr ductile cast iron is developed by taking three different combinations, viz. Heat-1, Heat-2 and Heat-3 of the selective amount of silicon, molybdenum, copper and chromium. For fracture toughness characterization, the specimens are prepared from the samples in "as-cast" conditions. The value of static fracture toughness obtained from the experiments for the specimen of Heat-2 with a fatigue pre-crack is $54.49 \text{ MPa}\sqrt{\text{m}}$, whereas, for the specimens of Heat-1 and Heat-3, the fracture toughness values are 47.52 and $39.48 \text{ MPa}\sqrt{\text{m}}$, respectively. The higher static fracture toughness may be attributed to the consistent nodule distribution within the matrix of ferrite and pearlite with lower microshrinkage porosity. According to the results obtained from finite element simulations with a fatigue pre-crack using the experimental data, the simulated results for fracture toughness are found in agreement with the results obtained from the experimental data.

Keywords: Ductile cast iron, nodularity, microstructure, single edge-notched beam, fracture toughness, FE simulations

INTRODUCTION

The engine components of modern automobiles, e.g., engine casings, exhaust manifolds, turbocharger casings, camshafts, etc., are designed to perform at high temperatures and are tested to the core to meet the tough standards of high strength to weight ratio at elevated temperature [1]. Engineers constantly endeavour to design new materials exposed to high temperatures and thermo-mechanical stresses [2–4]. Ductile cast iron with high silicon and molybdenum is the material that can maintain dimensional stability at very high temperatures of approximately 750°C and above [5–6]. Ductile cast iron contains higher silicon, chromium, and molybdenum to have optimum mechanical properties such as toughness, strength, high wear resistance and ductility [7]. The mechanical components are assumed to possess several micro cracks or voids within their body, which will remain within the component without any crack growth during regular operation under the action of safe load and the property of the material is known as fracture toughness [8]. Before the 2nd World

War, to avoid crack propagation, the design engineers adopted a higher safety factor while designing the machine components [9]. Toughness is a generalized term used as the energy absorbed by the material before fracture and is equal to the area under the stress-strain curve up to rupture point. K_{IC} , G_{IC} , J_{IC} and CMOD (Crack mouth opening displacement) are the four common types of fracture toughness measures given in available literature [10]. Salehnejad *et al.* compared the two different materials for exhaust manifolds and found that instead of yield strength, fracture toughness is the criteria for evaluating the material strength of a cracked component [10]. As far as the concern of

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fracture toughness of available grades of ductile cast iron (DCI), till now, researchers have done a lot of work to find out the fracture toughness of different available DCIs, and accordingly, it is used extensively in the various engineering applications.

The role of fracture toughness becomes more critical when the component surface has minor cracks or voids in the material itself. The propagation of cracks also depends upon the type of cracks. Hosdez *et al.* have noticed the curved crack front in the spheroidal graphite iron, which helps reduce the crack growth rate and has higher fracture toughness compared to compacted and flakes graphite iron [11]. For modelling the material's failure behaviour and low cycle fatigue resistance, Collini *et al.* have used the microstructure-based reference volume element approach and confirmed the results numerically and experimentally [12]. The ductile iron was tested at the mesoscale and found that the nodule count, stress concentration and local triaxiality are the major factors that considerably affect the ductile cast iron behaviour. A new type of cast iron consisting of a mixed matrix of proeutectoid ferrite and ausferrite microstructure was developed, which has high tensile and yield strengths, hardness and ductility similar to pearlitic and ferritic grades of DCI [13]. The material has been developed and tested for suspension parts subjected to dynamic loads. Delprete and Sesana characterized the mechanical properties of a Si-Mo-Cr DCI containing a high amount of chromium and investigated the high cycle and low cycle fatigue properties at high temperatures to establish the alloy for high-temperature applications in automotive components [3]. Tokunaga *et al.* have obtained the fine acicular ferrite in the matrix of ferritic ductile cast iron with the addition of nickel during the study of the effect of higher nickel content on ductile cast iron microstructure [14]. The effect of in-mould inoculant's composition on DCI's microstructure and fatigue behaviour are experimentally studied by Borsato *et al.* using metallographic techniques [15].

In this study, fracture toughness (K_{IC}) of a newly developed material, Si-Mo-Cr DCI, is obtained. The composition of Si-Mo-Cr iron is intentionally taken different from the composition of available grades of DCIs. According to the results obtained from FE simulations with a fatigue pre-crack using the experimental data, the simulated results for fracture toughness are found in agreement with the results obtained from the experimental data.

METHODOLOGY

Preparation of Ductile Cast Iron

For the development of Si-Mo-Cr DCI, the melting of charge material based on charge calculation was done in a 30 kW induction furnace, shown in Figure 1(a), having a capacity of 10 kg of molten metal, installed with an input line voltage of 415 V, 3-Phase, and 50 Hz. The requisite composition is usually obtained in the same manner as for regular ductile cast iron (DCI). Only carbon, silicon, molybdenum, and chromium content need to be adjusted for a suitable composition. The charge material consists of pig iron, ferrosilicon, ferromolybdenum and ferrochromium. Based on the charge calculation basis, pig-iron, ferro-chrome and ferro-silicon with a predetermined amount of steel scraps are heated to a temperature of approximately 1450°C with a superheat.

Ferro-molybdenum is added at the end of the melting process to the molten metal in the furnace to ensure a homogeneous distribution of Molybdenum in the melt for a high recovery rate. Magnesium treatment and inoculation of the molten material are done in the treatment ladle. The copper chips are added to the treatment ladle just before pouring into moulds, as shown in Figure 1(b and c). The as-cast specimens have circular ($\varnothing 20$ mm) as well as rectangular (30 mm $\times$ 20 mm) cross-section cavity shapes for the bars having 200 mm of length, as shown in Figure 1(d). The experiments are conducted for three heats, designated as Heat-1, 2, and 3, to study the effects of variation in alloying elements and to prepare a large number of test samples. The chilled samples of all the three different melts are tested for elemental composition using a Spark-based optical emission spectrometer and the actual chemical compositions on an average basis are tabulated in Table 1.

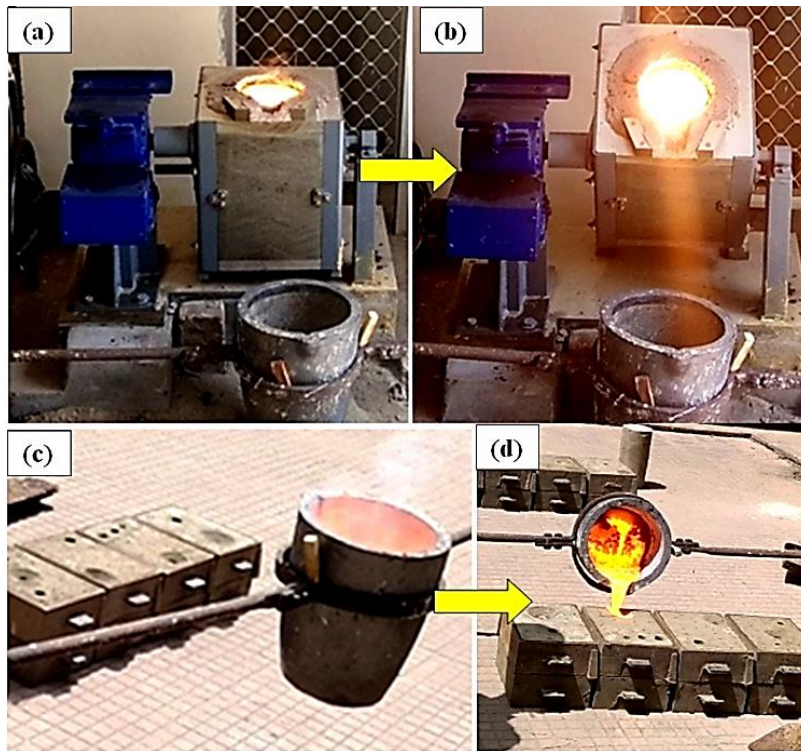


Figure 1. Preparation of DCI in induction furnace (a) melting of charge, (b) pouring of molten metal in the ladle, (c) magnesium treatment in the ladle and (d) pouring of moulds.

Table 1. Composition of as-cast Si-Mo-Cr DCI specimens in wt.%.

Heats	Major alloying elements								C_{eq}
	C	Si	Mo	Cr	Cu	Mg	P	Fe	
Heat-1	3.4	2.17	0.51	0.23	0.43	0.043	0.018	rest	4.12
Heat-2	3.42	2.96	0.64	0.32	0.38	0.054	0.016	rest	4.4
Heat-3	3.55	3.27	0.77	0.47	0.45	0.063	0.018	rest	4.63

Specimens for Fracture Toughness

Fracture toughness, a material property, presents essential information on the material behaviour under static loading conditions in the presence of a sharp natural crack. During the linear elastic behaviour of material before failure, when the size of the plastic zone developed is small as compared to the specimen dimensions, the critical value of stress intensity factor K_{IC} in the mode-I fracture is termed as fracture toughness of the material. The samples for fracture toughness, i.e., single edge-notched beam (SENB), are prepared by machining and surface finishing operations as shown in Figure 2. A notch size of 1.5 ± 0.05 mm in width and 7 ± 0.05 mm parallel depth ending with a V-notch of 1.5 mm in depth and with an included angle of 45° is prepared by the wire-cut electric discharge machining. Samples are prepared with a fatigue pre-crack located at the notch vertex to observe the effect of a sharp crack equivalent to a natural crack.

To analyse the scatter in results, specimens are prepared from the as-cast test bars obtained from each melt. A total of 27 test specimens are prepared with a sharp fatigue crack of zero openings. To prepare the specimens with a fatigue pre-crack of length, approximately 0.5 mm, initiated from the vertex of the notch root along the width of the specimens. The specimens are tested on a dynamic testing machine with 25 kN capacity (make: MTS, Model: 858 Table Top). The mean and amplitude loads used for fatigue pre-crack are 2200 and 1800 N, respectively, at a frequency of 20 Hz. The total number of cycles required for producing a pre-crack of the length of 0.5 mm is approximately 89,550 cycles.

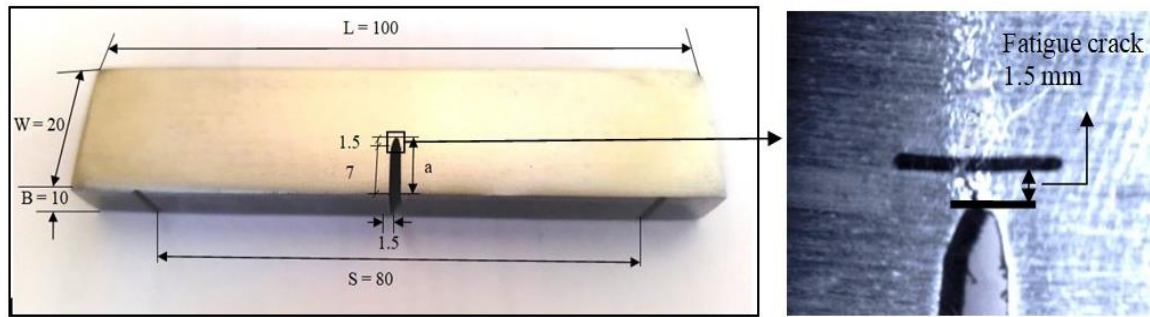


Figure 2. A standard specimen for the 3-point bend test.

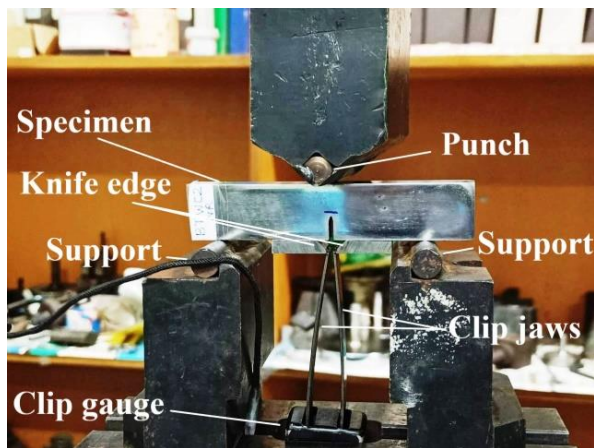


Figure 3. A setup for a 3-point bend test fixed on a dynamic testing machine.

Determination of Fracture Toughness

A common three-point bend test is performed as per the standard test procedure to determine the fracture toughness. The crack mouth opening displacement (CMOD) during the specimen loading in bending is measured using a clip-type gauge. For CMOD measurement, clip gauge jaws are rested against the knife edges attached to the specimen, as shown in Figure 3.

The knife edges are prepared separately by machining from a steel strip and attaching the specimen below the notch with a special adhesive along the length in such a way that the span length is not affected during bending. The knife edges are metallic strips of uniform thickness having an acute angle sharp edge at one end for attaching the arm of the clip gauge, as shown in Figure 3. The specimen is simply supported on the two roller supports and loaded in bending with the help of a roller punch fixed to the crosshead of the machine, as shown in Figure 3. The load, displacement, and CMOD data are recorded during the experiment by a data acquisition system attached to the machine.

Fracture toughness (K_{IC}) in-plane strain condition for material is determined by an equation given by Kumar and Prashant as given below [16]:

$$K_{IC} = \frac{3S\sqrt{a}}{2BW^2} Y\left(\frac{a}{W}\right) \cdot F \quad (1)$$

Where,

$$Y\left(\frac{a}{W}\right) = \frac{1.99 - \frac{a}{W}\left(1 - \frac{a}{W}\right)\left[2.15 - 3.93\frac{a}{W} + 2.7\left(\frac{a}{W}\right)^2\right]}{\left(1 + 2\frac{a}{W}\right)\left(1 - \frac{a}{W}\right)^{\frac{3}{2}}}$$

The force “ F ” is obtained from the force vs. displacement diagram obtained from the 3-point bend experiments, “ a ” is the initial crack length in mm, “ W ” is the height, and “ B ” is the thickness of the SENB specimen. “ S ” is the span length between two roller supports, as shown in Figure 3.

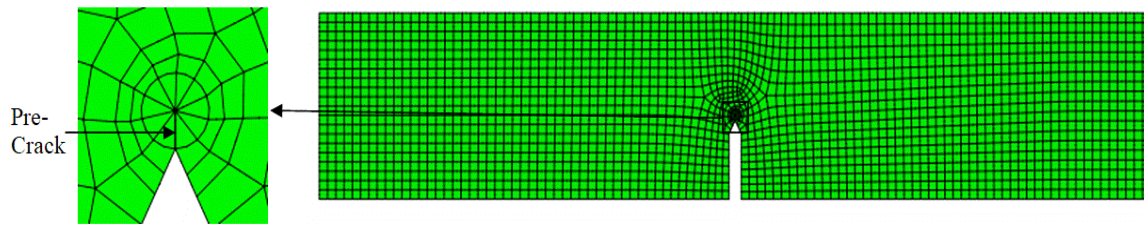


Figure 4. A meshed model of SENB specimen showing a pre-crack.

FE Simulations

Numerical simulation is carried out on a SENB specimen in bending using ABAQUS software. A crack is modelled at the notch using the contour integral method. The J -integral is calculated for the same while giving a displacement to the punch in the downward direction to load the specimen at the middle point on the top edge opposite to the crack tip. The reactive forces on the punch are also measured. The applied displacement in the simulations is taken from the data obtained from the 3-point bend tests.

Modelling and Meshing

To simulate the 3-point bend test, a deformable 2D SENB specimen is modelled as per the dimensions of the actual specimen shown in Figure 4. The material properties obtained from the uniaxial tensile experiments are assigned to the specimen. The section is assigned to the specimen with a plane stress/strain ratio of 10. The fatigue pre-crack of 0.5 mm is created in the interaction module using contour integral. A sharp crack is created at the notch tip by sketching a 0.5 mm section of zero thickness. A circle around the crack tip is sketched on the specimen surface and extended throughout the thickness. A seam is assigned at the partition above the notch for a crack. The crack extension direction is also selected in the '+y' direction with the help of q-vectors selected as the crack start and endpoints. A biased mesh is created in the crack tip as shown in Figure 4. Quarter-point nodes value of 0.25 with collapsed element side with the single node is also selected as element control for introducing the square root singularity at the crack tip. Quarter-point elements are used at the crack-tip to model the square-root singularity of the stress field ahead of the crack-tip. The stress intensity factor K_I (SIF) is calculated from the potential energy release rate or J integral using the expression in Eq. (2):

$$J = \frac{K_I^2}{\left(\frac{E}{1-\nu^2}\right)} \quad (2)$$

A plane strain state exists in the crack front region and the plane strain modulus ($E/(1-\nu^2)$) used in the expression, given in Eq. (2), is independent of the far-field stress state. J -integral, the potential energy release rate per unit of crack extension, being a global parameter, is less sensitive to inaccuracy in crack front elements computations. The path-independence property of J -integral is used to calculate an accurate value of J -integral by taking the contour in the region where finite element analysis yields more accurate calculations of displacements and stresses.

A 1 mm global seed is assigned to the specimen, while the local edge seeds are assigned in the circular region around the crack tip using quad-dominated sweep mesh controls. Quad element shape is assigned to the rest of the part of the specimen using quad elements and medial axis algorithm. Quadratic, reduced integral plane strain elements, CPE8R, are assigned to the whole specimen.

Boundary Conditions and Simulations

The SENB specimen is positioned in such a way that the two datum points at the bottom edge with a span of 80 mm (same as the distance between the two support pins in the actual experiment) by applying a boundary condition to restrict its vertical displacement during bending simulations. A static general step with geometric nonlinearity is selected for the step. The maximum number of increments with the initial increment, minimum increment and maximum increment values are set.

Two history outputs are created for the specimen and crack, respectively. In the history output for crack, J -integral is chosen with five numbers of contours. The load is applied in the '-y' direction during bending. In the experiment conducted to calculate fracture toughness, the load is found at which the crack starts growing, leading to fracture of the specimen. SIF calculated for the specimen geometry at the failure load is the critical fracture toughness or critical SIF of the material.

RESULTS AND DISCUSSION

Fracture Toughness

The force vs. CMOD plots obtained from the 3-point bend tests of the specimens with fatigue pre-crack are shown in Figure 5. The plot depicts a steep rise in bending load during the first part of the plot and then load decreases gradually, indicating the inability of the specimen to sustain the loads further due to crack propagation. During the 3-point bend test, specimens from Heat-2 undergo higher deflection at much higher bending loads, followed by the specimens of Heat-1 and Heat-3, respectively. As evident from the crack mouth opening displacement values, the crack propagates earlier in the specimens of Heat-3, followed by the specimens of Heat-2 and Heat-1. This could be attributed to the nodule numbers and geometry plays a significant role in arresting and disorienting the crack path.

The values of static fracture toughness obtained from the experiments for the specimens taken from Heat-1, Heat-2, Heat-3 and FE simulations are given in Table 2. The fracture toughness of the Heat-2 specimens is the highest with a value of $54.49 \text{ MPa}\sqrt{\text{m}}$, followed by the Heat-1 and Heat-3 specimens with fracture toughness values of 47.52 and $39.48 \text{ MPa}\sqrt{\text{m}}$, respectively. The results of fracture toughness values computed from the simulations for the samples of Heat-1, Heat-2 and Heat-3 are 49.17 , 56.56 , and $41.88 \text{ MPa}\sqrt{\text{m}}$, respectively and are found in good agreement with the results obtained from empirical relations using experimental data. The values of J -integral obtained from experimental data and simulations are also given in Table 2. The value of J -integral is highest for the specimens of Heat-2, followed by the specimens of Heat-1 and Heat-3. A similar trend is observed in the results obtained from the simulations. The variation of values of J -integral concerning CMOD obtained from experiments is also shown in Figure 6, which depicts the same trend as observed in Figure 5.

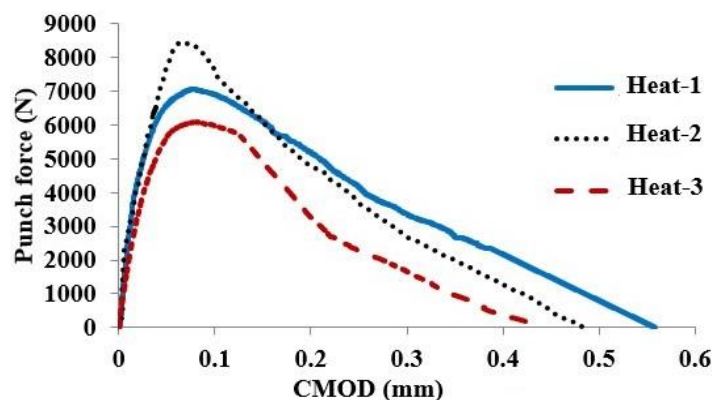


Figure 5. Punch force vs. crack mouth opening displacement plots.

Table 2. Comparison of experimental and simulation results.

Heat	Fracture toughness ($\text{MPa}\sqrt{\text{m}}$)		J-integral (N/m)	
	Experimental	Simulations	Experimental	Simulations
Heat-1	47.52	49.17	14061.38	15055.01
Heat-2	54.49	56.56	20064.85	20124.79
Heat-3	39.48	41.88	10528.96	10921.8

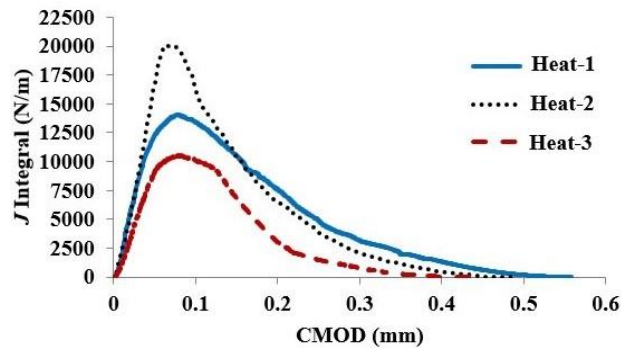


Figure 6. Variation of J-integral w.r.t. crack mouth opening displacement.

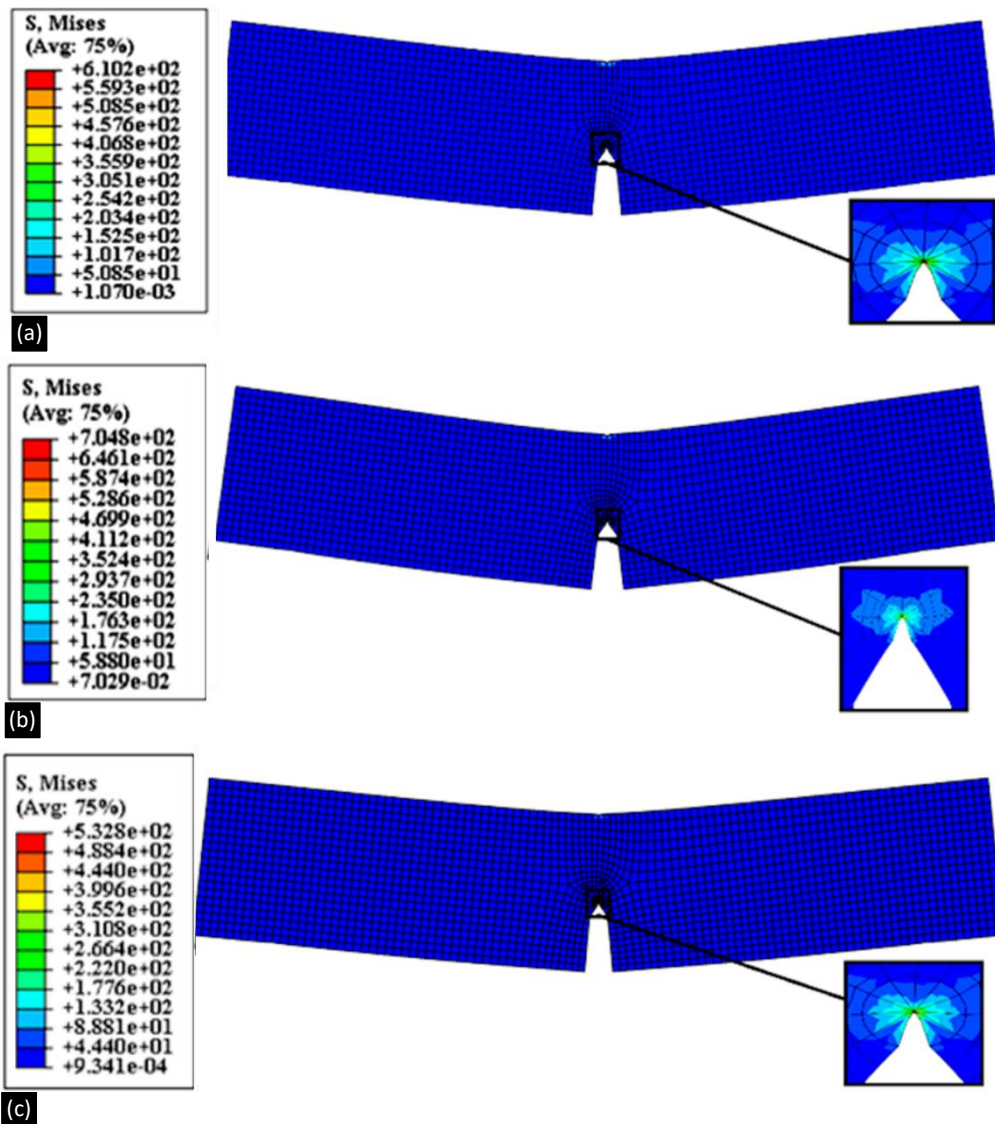


Figure 7. Simulation results showing variation in stress in SENB specimens of (a) Heat-1, (b) Heat-2, and (c) Heat-3.

The simulation results obtained from the 3-point bend tests of SENB specimens are shown in Figure 7 for Heat-1, 2, and 3, respectively. It is observed from the stress contour plots that the simulation results of bending of the specimen of Heat-2 show the maximum stress under the same deflection, followed by the bending simulation results of the specimens of Heat-1 and Heat-3,

respectively. This can be attributed to the tensile strengths of the respective materials. A tested SENB specimen is also shown in Figure 8. The tensile test experiments and the three-point bend test data are used in numerical simulation to determine the stress distribution in the SENB specimens. The values of J-integral are calculated from the resulting stress distribution. Thus, critical fracture toughness is calculated, which is observed to be close to the values from the experimental results.

Fractography

The variation in Si-Mo-Cr DCI properties is observed by microstructural analysis. The tested SENB samples are examined rigorously using a scanning electron microscope (SEM). All the tested samples showed an irregular fractured surface having uneven peaks and valleys, as shown in Figure 9. Some small inclusions are also observed in the micrograph.

The significant role is played by the spherical nodules in arresting the crack and reorient the crack path around the nodule as observed at higher magnification in the tested specimens of Heat-1 as shown in Figure 10. A fibrous cleavage appearance is also observed in the nodules as observed in Figure 10.

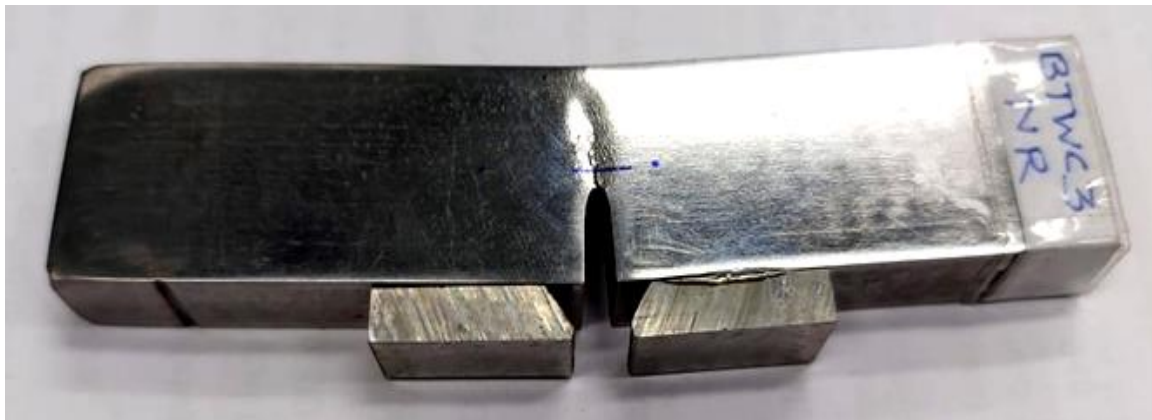


Figure 8. A tested SENB specimen.

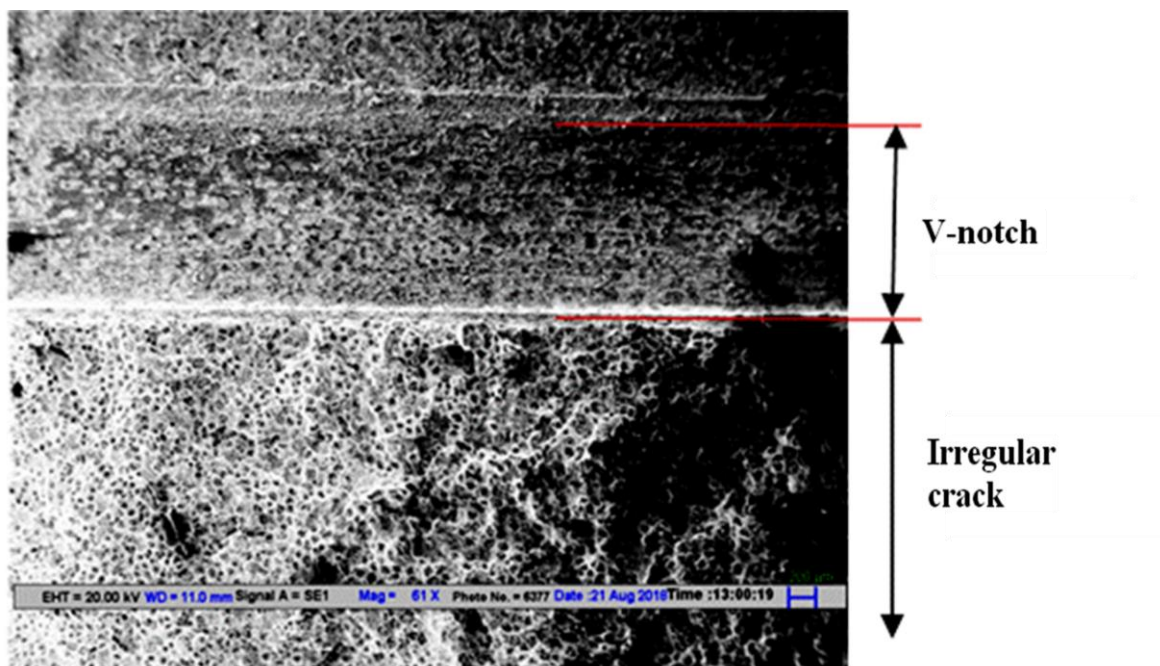


Figure 9. A micrograph showing a fractured surface with an irregular crack front.

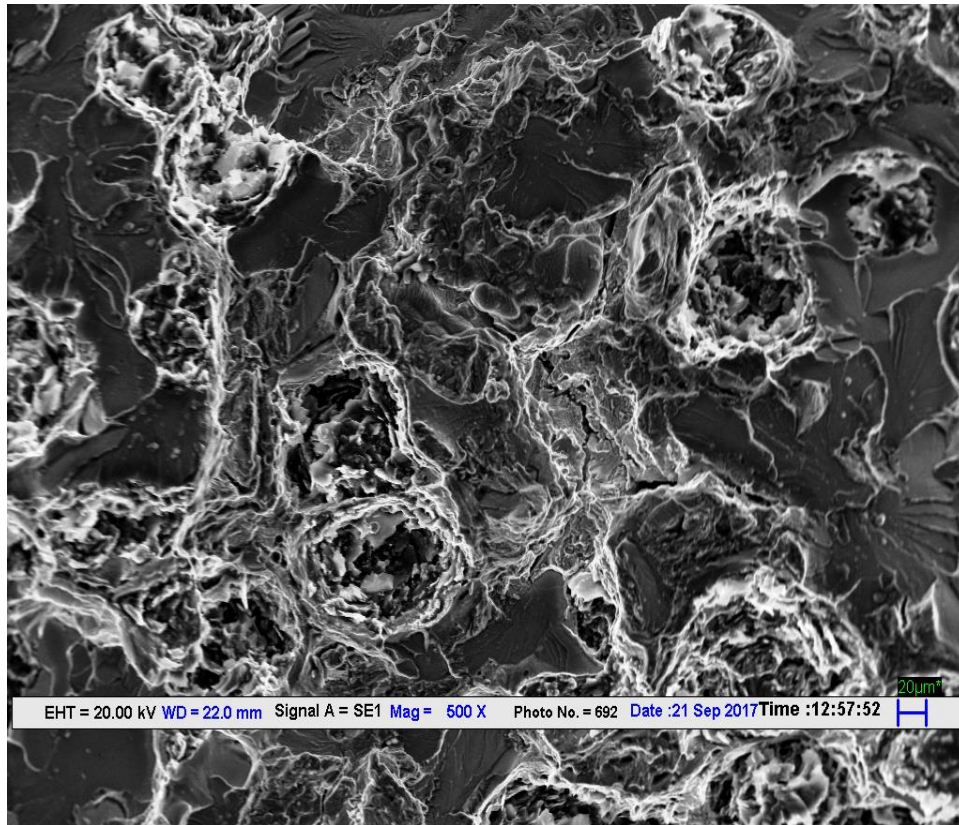


Figure 10. Crack path reorientation phenomenon in the specimen of Heat-1.

CONCLUSIONS

In the present study, a Si-Mo-Cr DCI material containing varying amounts of silicon, molybdenum, and chromium is developed in three different heats to characterize the fracture toughness in the specimens prepared from the sample in "as-cast" condition. The spherical nodules significantly arrest and reorient the crack path around the nodule, as evident from the results of scanning electron microscopy. The value of static fracture toughness obtained from the experiments for the specimen of Heat-2 with a fatigue pre-crack is $54.49 \text{ MPa}\sqrt{\text{m}}$, whereas, for the specimens of Heat-1 and Heat-3, the fracture toughness values are 47.52 and $39.48 \text{ MPa}\sqrt{\text{m}}$, respectively. The higher value of static fracture toughness of Heat-2 may be attributed to the homogeneous distribution of the nodules in the matrix of ferrite and pearlite with lower microshrinkage porosity. According to the results obtained from FE simulations with a fatigue pre-crack using the experimental data, the simulated results for fracture toughness are in agreement with the results obtained from the experiments.

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