JOURNAL OF MATERIALS SCIENCE 24 (1989) 3994–3999

# Fracture toughness of maraging steel from Charpy "V" notch specimens

V. DIWAKAR, S. ARUMUGAM, T. S. LAKSHMANAN, B. K. SARKAR
*Materials and Metallurgy Group, Vikram Sarabhai Space Centre, Trivandrum 695 022, India*

Compact tension (CT) and Charpy "V" notch (CVN) (impact and three-point bend) specimens of 18 Ni 1800 MPa maraging steel (parent metal and weldment) were used to determine plane strain fracture toughness ($K_{IC}$) and CVN impact energy (CVNIE), respectively. Using an empirical equation, $K_{IC}$–CVNIE correlation is attempted which could be advantageously utilized for routine quality control of inward material to effect savings in cost and time. Investigations reveal better $K_{IC}$–CVNIE correlation for tests using the precracked CVN specimens. Scanning electron microscopic (SEM) observations reveal good correlation between fractographic features and fracture toughness.

## 1. Introduction

The use of ultrahigh strength steels, such as 18 Ni 1800 MPa grade maraging steel, for launch vehicle applications has warranted a fracture-based design approach to avoid catastrophic failure. Plane strain fracture toughness, $K_{IC}$, is one of the important fracture parameters which are determined by ASTM E 399 [1] Standard. Compact tension (CT) specimens commonly used for $K_{IC}$ determination has intricate geometry, involves precision fabrication and has as many as six validity checks to be satisfied to arrive at the critical stress intensity factor all of which increase the time and cost element for a routine quality control (QC) of inward material. Hence there has been a constant pursuit to use specimens of simpler geometry to meet routine QC requirements at low time and cost elements. One significant attempt in this direction has been to use Charpy "V" notch (CVN) specimens to derive impact energy which can be correlated with $K_{IC}$ [2–5].

Rolfe and Barsom [6] suggested empirical relations using CVN upper shelf and transition region energy values with $K_{IC}$, as

$$\frac{K_{IC}^2}{\sigma_{YS}} = \frac{5}{\sigma_{YS}}\left(\text{CVN} - \frac{\sigma_{YS}}{20}\right) \quad (1)$$

$$\frac{K_{IC}^2}{E} = A\,(\text{CVN}) \quad (2)$$

where $K_{IC}$ is $10^3$ p.s.i. in.$^{1/2}$ yield strength is 0.2% proof stress at upper shelf or room temperature in $10^3$ p.s.i. and $E$ is Young's Modulus in $10^3$ p.s.i., and CVN in ft lb.*

Several authors [7–10] have used precracked CVN specimens for $K_{IC}$ evaluation. Ease of fabrication and testing are the advantages of CVN specimens over other geometries. Moreover it is possible to test a specimen taken from various locations in a billet, plate or a ring to arrive at a statistical variation of fracture toughness (FT). This paper reports the results and analysis of experiments carried out using CVN specimens for FT evaluation of 18 Ni 1800 MPa grade maraging steel (parent metal and weldment).

## 2. Experimental procedure and results

### 2.1. Materials and specimens

Tensile specimens [11], of standard size (10 mm × 10 mm × 55 mm), CVN specimens (SSCVN) [12] and three-point bend (TPB) and compact tension (CT) specimens [1] were fabricated from maraging steel rolled plate. Fig. 1 shows the lay-out of a specimen taken from the rolled plate. Keeping in mind the possible use of a particular thickness maraging steel plate for launch vehicle motor cases, another set of standard sub-size CVN specimens (SSSCVN) of 7.5 mm × 10 mm × 55 mm size were fabricated from 7.5 mm thick parent metal and welded plate. For both CT and CVN specimens from welded plate the notch was located at the fusion zone. All specimens were maraged at 753 K for 3.5 h before testing.

### 2.2. Testing

An Instron model 8033 testing machine was used for tensile and FT tests, whereas the impact test (IT) was done in a pendulum impact tester. Table I shows the tensile and FT data.

### 2.3. FT from CVN specimens

SSCVN and SSSCVN specimens were fatigue precracked as per ASTME 399 with $a/w$ ($a$ = crack length, $w$ = width of specimen) between 0.45 and 0.55 and satisfying the condition, $1 \leqslant W/B \leqslant 4$, and were tested by (a) TPB and (b) IT.

#### *2.3.1. TPB test*

The precracked CVN specimens were TPB tested as per ASTM E-399 with a span of 40 mm using an 8033 Model Instron testing machine and bend fixture.

*$10^3$ p.s.i. = 6.89 N mm$^{-2}$, 1 ft lb = 1.3558 Nm.


0022-2461/89 $03.00 + .12

TABLE I 18 Ni 1800 MPa maraging steel
(a) Tensile properties

| No. | UTS (MPa) | 0.2% YS (MPa) | % Eln 0.05 MGL | Remarks |
|---|---|---|---|---|
| 1. | 1840 | 1775 | 10.4 | Parent metal |
| 2. | 1674 | 1619 | 8.0 | Weldment |

(b) Fracture toughness, CT specimens, $W = 2B$.

| No. | Orientation | $K_Q$(MPa m$^{½}$) | Remarks |
|---|---|---|---|
| 1. | LT | 93.7 | Parent metal |
| 2. | TL | 94.5 | |
| 3. | – | 84.2 | Weldment |
| 4. | – | 85.3 | |
| 5. | – | 85.3 | |

From the load against load point displacement plot (which correspond to Type III plot of ASTM E-399), the maximum load was taken for FT calculation. The crack length, $a$, was measured on tested halves of the specimens. The stress intensity, $K_Q$, was evaluated [1] as

$$K_Q = \frac{P_Q f(a/w)\, S}{BW^{3/2}} \tag{3}$$

where $K_Q$ is the conditional stress intensity factor, $P_Q$ is 5% secant or maximum load at this point, $f(a/w)$ is a compliance function, $B$ is the thickness, $W$ the width and $S$ the span. Table II shows FT values of parent metal and weldments from the TPB test.

TABLE II 18 Ni 1800 MPa maraging steel - fracture toughness derived from Equation 3 using precracked CVN specimen tested in three point bend test
(a) Parent metal (solution treated and maraged)

| No. | Orientation | $K_Q$(MPa m$^{1/2}$) | Remarks |
|---|---|---|---|
| 1. | LT | 103.4 | 10 mm × 10 mm × 55 mm |
| 2. | LT | 100.0 | CVN specimens |
| 3. | LT | 102.5 | |
| 4. | LT | 104.6 | |
| 5. | LT | 100.9 | |
| 6. | TL | 96.7 | |
| 7. | TL | 92.6 | |
| 8. | TL | 97.2 | |
| 9. | TL | 97.7 | |
| 10. | TL | 99.0 | |
| 11. | TL | 92.0 | |
| 12. | TL | 93.1 | |
| 13. | TL | 93.1 | |
| 14. | TL | 92.1 | |
| 15. | LS | 90.0 | |
| 16. | LS | 90.7 | |
| 17. | LS | 99.9 | |
| 18. | LS | 95.6 | |
| 19. | LS | 93.5 | |
| 20. | LT | 100.6 | 7.5 mm × 10 mm × 55 mm |
| 21. | LT | 100.6 | CVN specimens |
| 22. | TL | 93.4 | |
| 23. | TL | 95.3 | |
| 24. | TL | 97.2 | |

(b) Weldment (welded and maraged)

| No. | $K_Q$, MPa m$^{1/2}$ | Remarks |
|---|---|---|
| 25. | 83.2 | |
| 26. | 85.9 | 7.5 × 10 × 55 mm |
| 27. | 80.8 | CVN specimens |
| 28. | 91.1 | |
| 29. | 89.5 | |
| 30. | 96.9 | |

TABLE III 18 Ni 1800 MPa maraging steel – fracture toughness derived from Equation 4 and using impact tests on precracked CVN specimen parent metal (solution treated and maraged)

| No. | Orientation | $K_Q$(MPa m$^{1/2}$) | Remarks |
|---|---|---|---|
| 1. | LT | 100.5 | SSCVN |
| 2. | TL | 107.9 | specimens |
| 3. | LS | 111.6 | |
| 4. | LS | 116.8 | |
| 5. | LT | 107.7 | SSSCVN |
| 6. | LT | 108.8 | specimens |

### 2.3.2. *Impact test*

Using the impact energy, $U$, and the crack length, $a$, obtained from the impact test, FT was estimated using the equation [13, 14]

$$\frac{K_{IC}^2}{E} = \frac{1}{2\,(1 - \nu^2)}\,\frac{U}{A} \tag{4}$$

where $E$ is Young's modulus, $\nu$ is Poisson's ratio and $A$ is the cross sectional area, i.e. $(B\text{-}a)W$. Table III shows FT values obtained from the impact test.

## 2.4. FT from empirical equation

It has been shown [15, 16] that 18 Ni 1800 MPa grade maraging steel does not exhibit a ductile brittle transition temperature (DBTT) curve, unlike carbon steels. The DBTT curves for maraging steel are almost straight lines from 123 to 773 K. Experiments conducted in house [17] have also revealed a straight-line behaviour from 143 K to room temperature. Equations 1 and 2 are for correlation of $K_{IC}$ and upper shelf and transition region CVN values for carbon steels which exhibit DBTT, whereas 18 Ni 1800 MPa maraging steel falls at the foot of the $K_{IC}$–CVN upper shelf region as given in the literature [6]. The constants of Equations 1 and 2 are modified to suit the metric units of CVN, yield strength and Young's modulus:

$$\frac{K_{IC}^2}{\sigma_{YS}} = \frac{0.5}{\sigma_{YS}}\left[\mathrm{CVN} \times 10^3\left(-\frac{\sigma_{YS}}{0.33}\right)\right] \tag{5}$$

and

$$\frac{K_{IC}^2}{E} = 0.3\,(\mathrm{CVN}) \tag{6}$$

the results of which are given in Table IV.

## 2.5. Fractography

Carl Zeiss Jena Citoval Zoom Stereomicroscope and a Cambridge Stereoscan Model 250 MK3 scanning electron microscope (SEM) were used to study fracture surfaces of specimens tested in impact and TPB for both parent metal and weldments. Fig. 2 shows schematic diagrams of fracture surfaces indicating the locations from which SEM fractographs were obtained as in Figs 3 to 12.

# 3. Discussions

## 3.1. FT from tests

From the tensile and FT data for parent metal and

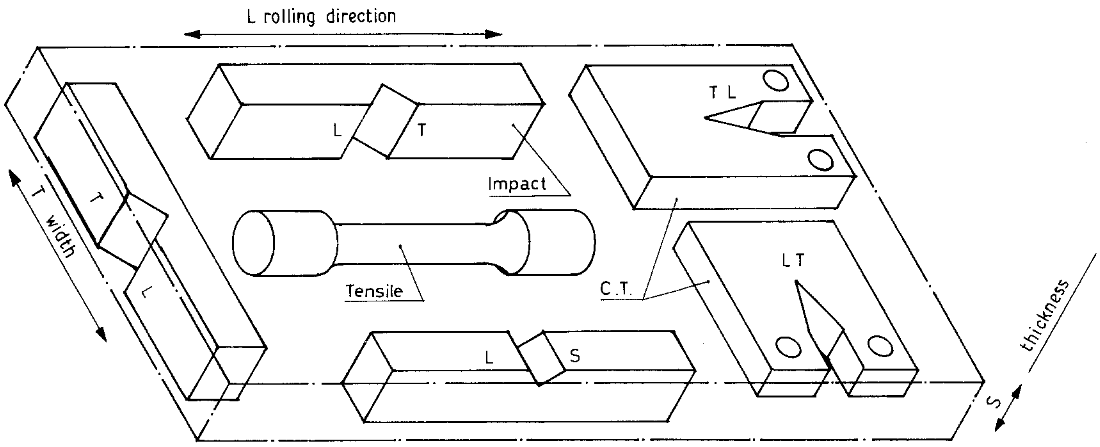



*Figure 1* Lay-out of specimen in the plate.

weldment in Table I, it is seen that 90% efficiency was achieved in the weldment with respect to ultimate tensile strength (UTS) and FT. The FT is 94 MPa $m^{1/2}$ for parent metal and 85 MPa $m^{1/2}$ for weldment.

Table II shows the FT values derived from TPB slow bend tests on precracked CVN specimens. The FT values derived from SSCVN specimens range from 100.0 to 104.6 MPa $m^{1/2}$ with an average of 102.3 MPa $m^{1/2}$ in the LT direction. Similar results are obtained in CT specimens for the LT direction (Table I). In the TL direction it varies from 92.0 to 99 MPa $m^{1/2}$ with an average of 94.85 MPa $m^{1/2}$. The CT specimens in the TL direction yielded 94.5 MPa $m^{1/2}$. The FT in LS orientation varies from 90.0 to 99.85 MPa $m^{1/2}$ with an average of 93.9 MPa $m^{1/2}$. The FT of parent metal derived from SSSCVN specimens yielded an average of 100.6 MPa $m^{1/2}$ in LT and 95.3 MPa $m^{1/2}$ in TL orientation. Therefore, for the parent metal, variation in FT derived from SSCVN and SSSCVN specimens is only $\pm 5\%$. This suggests that it is possible to use a parent metal SSSCVN specimen of 18 Ni 1800 MPa grade maraging steel to derive FT because both configurations seem to impose the same constraints with respect to plastic zone size at the notch tip, thus leading to small variation [18]. Similarly, for weldments, FT values vary from 80.8 to 96.9 MPa $m^{1/2}$ with an average at 88 Mpa $m^{1/2}$, less than 5% from that obtained using welded CT specimen.

Table III shows FT values derived from $U$ and $K_{IC}$ (Equation 4). The parent metal FT for SSCVN ranges from 100.3 to 116.80 Mpa $m^{1/2}$ with an average of 106.5 Mpa $m^{1/2}$ and for that for SSSCVN specimen is 108 MPa $m^{1/2}$. The impact strength for the two configurations shows no appreciable variation. The percentage FT variation between minimum and maximum is only 1.5%. However, when these values are compared with those obtained fron CT specimens, the variation is about 15% which can be attributed to different conditions of static (CT) and dynamic (impact) testing.

Table IV shows that for SSSCVN specimens the derived FT of weldment is about 1.1 times that for parent metal because the impact test causes dynamic opening out for possible crack propagation from the notch tip through a heat-affected zone (HAZ) of

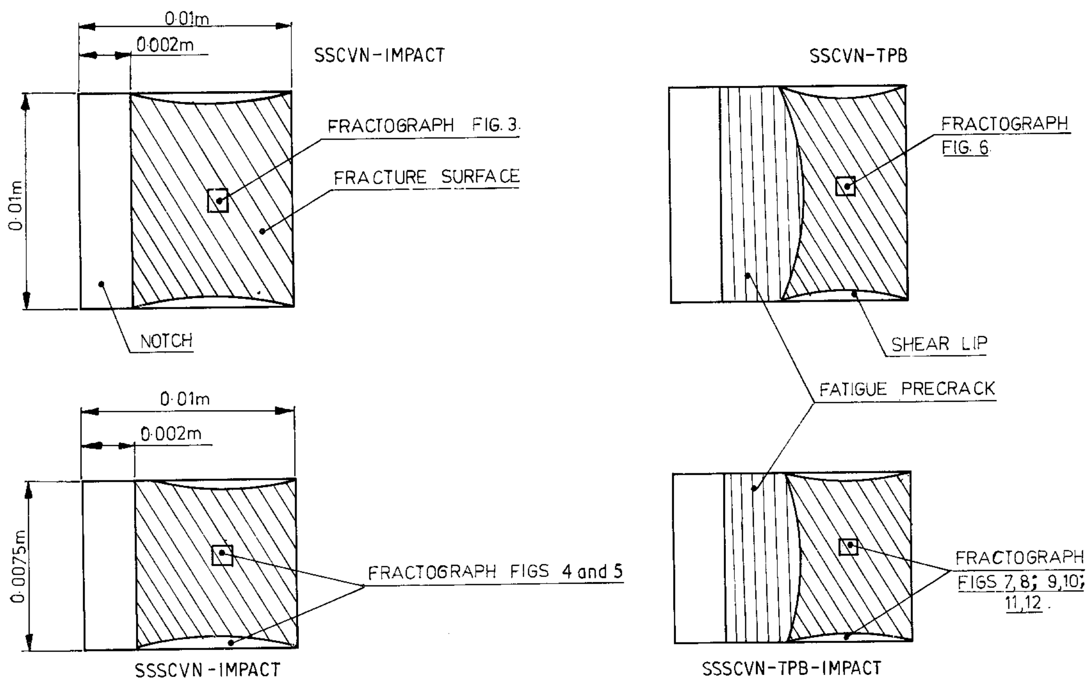



*Figure 2* Schematic diagram of fracture surface of SSCVN and SSSCVN specimens.

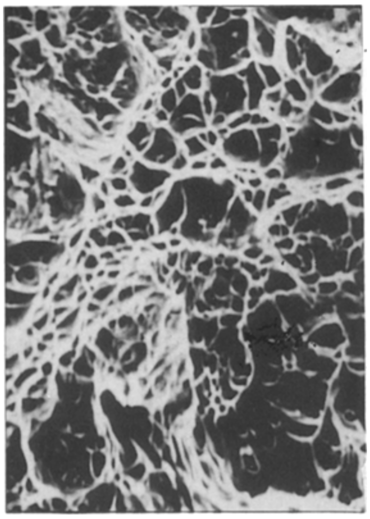


*Figure 3* Fracture surface of SSCVN (parent metal) impact tested; (SEM) × 1000.

TABLE IV 18 Ni 1800 MPa maraging steel – fracture toughness derived from CVN impact test using empirical equations

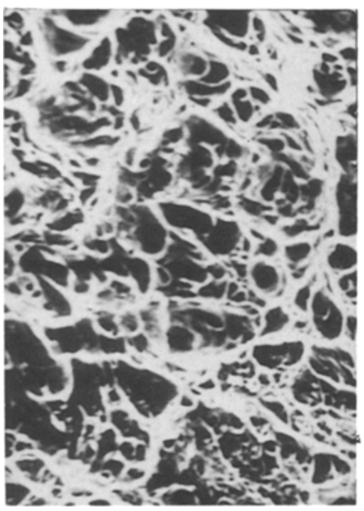
| No. | $K_Q$(MPa m$^{1/2}$) (Equation 5) | $K_Q$(MPa m$^{1/2}$) (Equation 6) | Remarks |
|---|---|---|---|
| 1. | 98.6 | 97.3 | Parent metal SSCVN specimen |
| 2. | 106.0 | 102.3 | |
| 3. | 106.0 | 102.3 | |
| 4. | 101.8 | 99.4 | |
| 5. | 80.2 | 85.3 | Parent metal SSSCVN specimen |
| 6. | 87.9 | 90.3 | |
| 7. | 80.2 | 85.3 | |
| 8. | 97.8 | 97.4 | Weldment SSSCVN specimen |
| 9. | 91.5 | 93.0 | |
| 10. | 97.8 | 97.4 | |
| 11. | 97.8 | 97.4 | |
| 12. | 95.7 | 96.0 | |
| 13. | 93.6 | 94.5 | |
| 14. | 95.7 | 96.0 | |
| 15. | 99.8 | 98.8 | |
| 16. | 101.7 | 100.3 | |

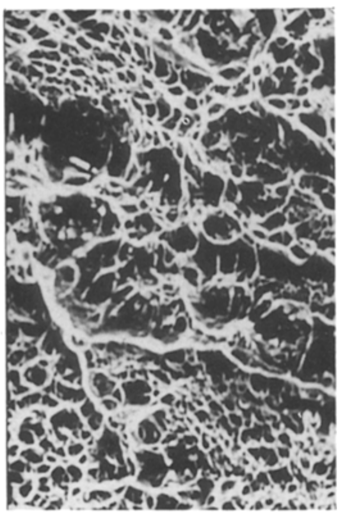
weldment having higher FT [19–21]. This has resulted from the fact that the HAZ is very near the weld fusion line (less than 1 mm) and that HAZ has an angular configuration for "V" groove weldment used in the present study. On the other hand, in the TPB test, owing to static opening out from the precrack at the notch tip, the crack propagation is through the weld fusion zone which has lower FT values (Table II) compared to the parent metal. It is also clear from Table IV that variation of $K$ derived from CVNIE using Equations 5 and 6 is within 10% over FT (Table I) obtained from CT specimens for both parent metal and weldments.

It was found that for parent metal, FT values for SSCVN specimens yielded valid $K_Q$, i.e. $K_{IC}$, but for parent metal SSSCVN specimens, $K_Q$ was found to be above 94 MPa m$^{1/2}$, and for weldments, $K_Q$ was above 90% of 94 MPa m$^{1/2}$, i.e. 85 MPa m$^{1/2}$ did not satisfy the thickness criterion for 7.5 mm. However, those $K_Q$ values are included for discussion of the results. It is understood that the material is thus capable of tolerating a crack larger than the critical crack size for the particular plate thickness, indicating higher toughness and therefore it is assumed to be safe from the design point of view.

### 3.2. Fractography

Fracture surfaces of impact tested SSCVN and SSSCVN specimens and also TPB-tested SSCVN and SSSCVN specimens (all parent metal) show equiaxed dimples (Figs 3 to 8) indicating microvoid coalescence as the fracture mechanism [22–23] thus enabling us to correlate the data between SSCVN and SSSCVN specimens. Fracture surfaces of SSSCVN weldment for TPB and impact tests are shown in Figs 9 to 12. An interesting observation is that fractographic features are identical for those specimens which yield higher (parent metal TPB-tested and weldment impact-tested as in Figs 7 and 11) or lower (parent metal impact-tested and weldment TPB- tested as in Figs 4 and 9) FT values. The sheer lip portion of impact and TPB-tested parent metal and weldments (all SSSCVN specimens) are shown in Figs 5, 8, 10 and 12. Irrespective of the static (TPB) or dynamic (impact) nature of testing, it is seen that the parent metal exhibits finer microvoids (Figs 5 and 8) whereas the weldments (Figs 10 and 12) show coarser dimples. The fractograph studies lead us to conclude that the morphology of the fracture surface away from the notch (impact test) or precrack (TPB test), as the case may be, gives an indication of the magnitude of fracture toughness.





*Figures 4 and 5* Fracture and shear lip surfaces of SSSCVN (parent metal), impact tested, (SEM) × 1000.

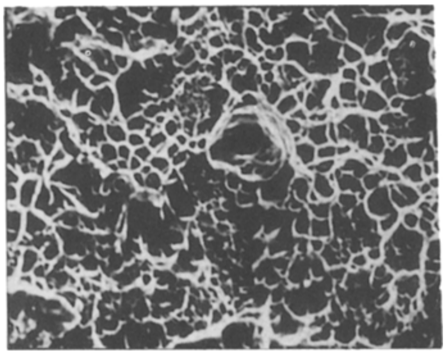


*Figure 6* Fracture surface of SSCVN, TPB tested, (parent metal), (SEM) × 1000.

## 4. Conclusion

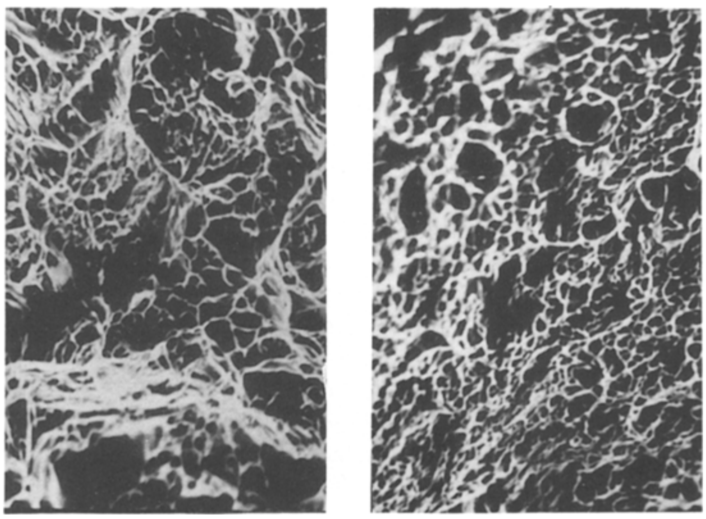
The TPB (slow bend) test using precracked SSCVN specimens and Equation 3 yielded average $K_{IC}$ of 102.3, 94.9 and 93.9 MPa m$^{1/2}$, respectively for LT, TL and LS directions for the parent metal. For the precracked SSSCVN specimen, FT was found to be 95.3 MPa m$^{1/2}$ for the parent metal in the TL direction and 88.0 MPa m$^{1/2}$ for the weldment. These values are within ±5% from that obtained using CT specimens for parent metal and weldment. The impact tests on precracked specimens and Equation 4 yielded an average parent metal FT of 108.5 MPa m$^{1/2}$ which is about 15% higher than that obtained from CT specimens. Empirical Equations 5 and 6 and the impact test yielded FT values which vary by ±10% from that obtained using CT specimens for both parent metal and weldment.

Considering the low quantum of material involved and ease of fabrication, CVN specimens are found to be the simplest geometry for FT evaluation. Present investigations on 18 Ni 1800 MPa grade maraging steel, reveal that, out of the three methods, i.e. slow bend and impact test both using precracked CVN specimens and empirical correlation from CVN impact test, the slow bend test on precracked CVN specimens provides the best method to arrive at FT for routine QC of inward material.

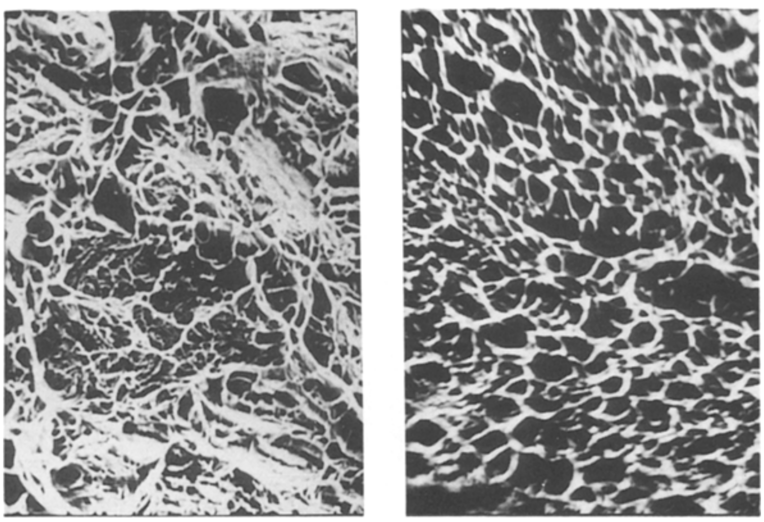
The morphology of the fracture surface away from the notch/precrack, as the case may be, for impact/TPB tests, correlates very well with magnitude of fracture toughness.

## Acknowledgements

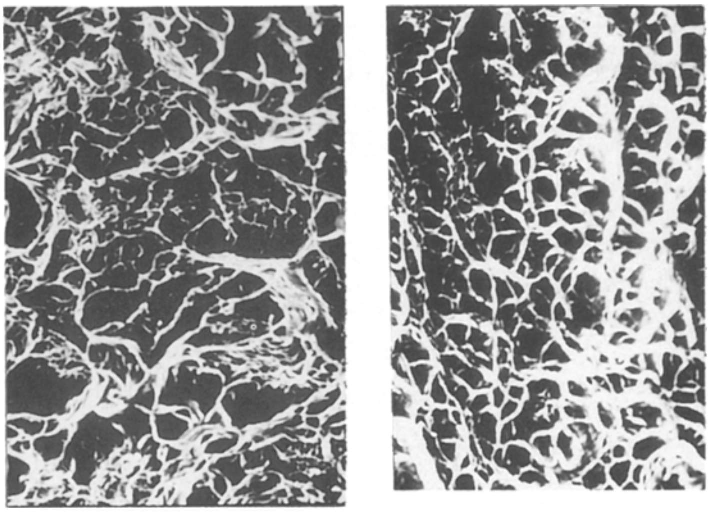
The authors thank Shri Easwaradas, Deputy Director, VSSC (Materials and Mechanical Systems) for his encouragement in this work, and the Metallurgy and Ceramics Division (MAC) and External Fabrication



*Figures 7 and 8* Fracture and shear lip surfaces of SSSCVN (parent metal), TPB tested, (SEM) × 1000.



*Figures 9 and 10* Fracture and shear lip surface of SSSCVN (weldment), TPB tested, (SEM) × 1000.



*Figures 11 and 12* Fracture and shear lip surface of SSSCVN, (weldment), impact tested, (SEM) × 1000.

Activities for supply of specimens and MAC for extending SEM facility. The authors also thank Dr S. C. Gupta, Director, for his permission to publish this paper.

## References


1. "Standard Method for Plane Strain Fracture Toughness Evaluation of Metallic Materials", Annual Book of ASTM Standards, ASTM E 399–81 (American Society for Testing and Materials, Philadelphia, Pennsylvania, 1981) p. 588.
2. J. M. BARSOM and S. J. ROLFE, "Impact Testing of Materials", ASTM STP 466 (American Society for Testing and Materials, Philadelphia, Pennsylvania, 1970) p. 281.
3. D. P. CLAUSING, *Int. J. Fract. Mech.* **6** (1) (1970) p. 71.
4. J. H. HOLOMAN, *Trans. AIME* **158** (1944) 310.
5. S. T. ROLFE and S. R. NOVAK, "Slow Bend $K_{IC}$ Testing of Medium Strength High Toughness Steels", ASTM STP 463 (American Society for Testing and Materials, Philadelphia, Pennsylvania, 1970) 124.
6. S. T. ROLFE and J. M. BARSOM, "$K_{IC}$–CVN Upper Shelf Correlation, Fracture and Fatigue Control in Structures, Application of Fracture Mechanics" (Prentice-Hall, New Jersey, 1977) p. 174.
7. T. M. F. RONALD, J. A. HALL and C. M. PIERCE, *Met. Trans.* **3** (1972) 813.
8. A. S. TETELMAN, T. N. ROBINSON and I. ROMAN, in "The Use of Small Precracked Specimens for QC Purposes, Prospects of Fracture Mechanics", edited by G. S. Sih, H. C. Vaneist and D. Broek, (Noordhaf, The Netherlands, 1974) p.563.
9. F. J. WIKT, "Instrumented Precracked Charpy Testing", EPRI- NP-2102-LD, Project 1757–1, CSNI No. 67, Proceedings (November 1981) EPRI, California, pp. 4–131.
10. T. VARGA and D. M. NJO, *ibid.*, pp. 1–65.
11. "Standard Methods of Tension Testing of Metallic Materials", ASTM E 8–81, Annual Book of ASTM Standards, Part 10 (American Society for Testing and Materials, Philadelphia, Pennsylvania, 1981) p. 197.
12. "Standard Methods for Notched Bar Impact Testing of Metallic Materials", ASTM E 23–81, Annual Book of ASTM Standards, Part 10 (American Society for Testing and Materials, Philadelphia, Pennsylvania, 1981) p. 273.
13. R. W. HERTZBERG, "Deformation and Fracture Mechanics of Engineering Materials", 2nd Edn (Wiley, N.Y., 1983) p. 339.
14. T. J. KOPPENALL, "Instrumented Impact Testing", ASTM STP 563 (American Society for Testing and Materials, Philadelphia, Pennsylvania, 1974) pp. 92–117.
15. Firth Brown, "Maraging Steels, Data Book" (Firth Brown, Sheffield, 1976).
16. Inco Data Book, "18% Nickel Maraging Steels, Engineering Properties" (INCO Europe Ltd., London, 1976).
17. V. DIWAKAR, Impact Test on Maraging Steel at Low Temperature", Technical Report, VSSC–MMS–MMG–TAF–4–86 (October 1986).
18. "CVN Impact Test as an Alternative to ASTM EA–399 FT Test", VSSC Technical Report, VSSC : MMS : CVN–$K_{IC}$ : 1 : 88 (January 1988).
19. C. K. KRISHNADASAN, "Studies on Heat Affected Zones in Maraging Steel", VSSC Technical Report, PSLV–VSSC–PR–STR–34–87 (March 1987).
20. J. G. BLAUEL, H. R. SMITH and G. SCHULZE, *Welding J. Res. Suppl.* **53** (1974) 8.
21. B. Z. WEISS, H. D. STEEFFENS and K. SEIFERT, *Welding J. Res. Suppl.* **51** (1972) 449.
22. ASM Metals Hand Book, "Fractography", Vol. 12, 9th Edition (ASM, Metals Park, Ohio, 1987).
23. K. P. DATTA and W. E. WOOD, "Fractography and Materials Science", ASTM STP 733 (American Society for Testing and Materials, Philadelphia, Pennsylvania, 1981), 150.


*Received 25 March 1988*
*and accepted 14 February 1989*