

HALL-PETCH DEPENDENCE OF DYNAMIC CRITICAL STRETCH ZONE WIDTH FOR A THERMALLY EMBRITTLED RPV STEEL

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Abstract. *In this study, thermally embrittled microstructures of a reactor pressure vessel steel were impacted in a Charpy testing machine and the critical stretch zone width of the precracked and sidegrooved specimens was measured and tentatively correlated to the representative cell size of materials tested. Charpy bend bar specimens (10x10x55mm^3) were machined from T/4 position of thick forged plates, in T-L orientation, then fatigue precracked to 0.5 nominal crack length to specimen width ratio and side-grooved with a Charpy cutter to 33% reduction in their gross-thickness. Bend bar specimens were dynamically tested at 300°C in an instrumented Charpy testing machine using a 300 J hammer at an impact velocity of 5.5 m/s. The mechanisms of initial fracture (blunted fatigue crack tip) were revealed by using a scanning electron microscope operating in both the secondary and backscattered electron imaging modes at accelerating voltage of 20 kV. The relationship between the critical values of stretch zone width and the representative cell size (RCS) of the microstructures tested, namely dual-phase annealed ferrite/bainite and single-phase Q&T bainite or martensite, has been shown to follow a Hall-Petch dependence.*

Keywords. *Charpy impact testing, Hall-Petch relationship, quantitative fractography, RPV steel, stretch zone width.*

1. Introduction

The elastic-plastic fracture process from a pre-existing crack in a monotonically loaded test specimen or structure consists of several stages, as noted by Pluvinage & Lanvin (1993): crack tip blunting, plastic zone formation at crack tip, nucleation and growth of voids ahead of crack tip, coalescence of voids, i.e., crack growth, along with the development of plastic wake, and final rupture.

Just before crack initiation, which corresponds to the coalescence of the original crack tip with the nearest void, crack stretching is an important step of the fracture phenomenon. Observed on the scanning electron microscope (SEM), this particular region exhibits a typical featureless appearance, which in most cases can be distinguished from the prior precrack surface and the subsequent main fracture by ductile tearing.

Since the critical stretch zone width (SZW_C) is an indicative of the extent of the plastic blunting of the crack tip, it offers an alternative method for determining a fracture toughness parameter that can be correlated with the critical values of energetic and geometric-based fracture mechanics parameters, J_{IC} (J-integral) and $CTOD_C$ (crack tip opening displacement) respectively.

The main advantage of SZW_C over other fracture toughness indexes is that no load, displacement or any other operational parameters need to be known. This is particularly important in post-mortem failure assessment or when load and displacement are absent or difficult to determine, which include the case of fracture toughness determination under dynamic loading conditions, where it is not possible or at least feasible to apply the standard J-R curve approach, e.g. by compliance or potential drop measurements, in order to determine the onset of crack growth.

Furthermore, it does seem interesting to have a permanent record that can be verified independently in various laboratories, in round robin programmes, so long as the permanent plastic strains on the fracture surface are the memory of the failure process. In this regard, the stretch zone width has been claimed to be an effective back-up technique for characterization of the fracture toughness of metals and weldments.

Hertzberg (1991) and Broek (1989) provide a comprehensive appraisal of the practical usefulness of the stretch zone width concept in failure analysis investigations.

In the present study, several thermally embrittled microstructures of nuclear grade steel were impacted in a Charpy testing machine and the SZW_C of the precracked and sidegrooved test specimens was measured and tentatively correlated to the representative cell size of the tested materials.

2. Materials

Basically, the A508 Class 3A steel is an exceptionally high-toughness microalloyed RPV material designed for the nuclear industry, with the as-received material (named A) exhibiting a granular bainite microstructure. Additionally, two classes of thermally embrittled materials were obtained and tested, namely, dual-phase ferrite/bainite annealed microstructures (nominated from B to H), and tempered martensite or bainite (from I to N) produced by quenching and tempering (Q&T). All these microstructures have been fully characterized by Tarpani et all (2003).

3. Experimental and analytical procedures

Charpy bend bar specimens (10x10x55 mm^3) were machined from thick forged plates (T/4 position, in T-L orientation) of the microalloyed steel in the as-received and thermally embrittled conditions. The samples were fatigue precracked to 0.5 nominal crack length to specimen width ratio (*a*/W), then side-grooved (SG) with a Charpy cutter to 33% reduction in their gross-thickness, B_G, towards a theoretically maximum plastic-constraint according to analysis performed by Zhang & Shi (1992). Special care was taken during the precracking procedure in order to comply exactly with the requirements established in ASTM standards (1997) regarding to the maximum stress intensity factor-K developed at the crack tip, thus avoiding introduce bias during the SZW_C generation.

Bend bar specimens were tested under dynamic loading at 300°C in an instrumented Charpy testing machine using a 300 J hammer at an impact velocity of 5.5 m/s.

The mechanisms of initial fracture (blunted fatigue crack tip) were revealed by using a SEM operating in both the secondary (SE) and backscattered (BSE) electron imaging modes at accelerating voltage of 20 kV. All the SEM fractographs were taken in such a way that the specimens were oriented at 90° to the incident electron beam (without tilting the specimens). The micrographs were picked up at the center of the specimens (0.33 B_G to 0.66 B_G positions), along the crack front, as instructed by Hyatt & Matthews (1994). The SZW_C values were accurately determined from the micrographs by means of a computerized image analyzer. As a general rule, the SZW_C results provided herein correspond to the average value of five evenly spaced measurements performed along the fatigue crack tip over the third center of each specimen. As previously shown by Bassim et all (1992), the three-points approach produces very similar results than the nine-points approach for typical Charpy specimen thickness, and so the adequacy of the five-points approach here adopted is guaranteed.

4. Results and discussion

Figure (1a) shows typical stretch zone formed during impact fracture of the as-received microstructure (A). Fatigue precracked zone and final fracture region by ductile tearing are also indicated. A higher magnification view of the SZW_C in this microstructure is supplied in Fig. (1b).

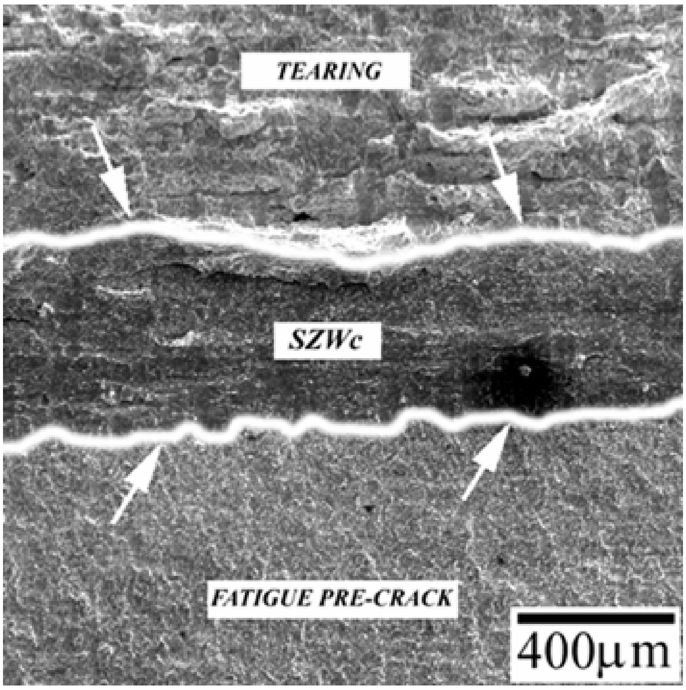
Figure (2) shows micro-fractographs referring to the SZW_C generated in the annealed (D and F) and Q&T (L and M) microstructures, respectively. The width of the stretched zones created in the thermal conditions D, F, L and M are substantially narrower than in the as-received material (A), thus signalizing that the heat treatments applied to the steel successfully impaired its original fracture toughness. It can be noticed that, under certain circumstances, BSE technique provides much better image definition than the well-recognized SE method. As a matter of fact, during the course of this study, it became clear that both the methodologies should be used in order to define within proper accuracy the SZW_C contours.

Figure (3) shows the relationships between the SZW_C values and the representative cell size (RCS) of the studied microstructures. Very good data correlation is noticed for both classes of materials. According to the definition adopted by Tarpani et all (2003), the RCS value corresponds to the bainite packet size in the quenched and tempered (Q&T) microstructures A, J, L and N, whereas RCS is the martensite packet size in the Q&T microstructures I, K and M. Still regarding this issue, for dual-phase annealed microstructures (B-H), RCS has been taken as the volume-fraction weighted average of the grain sizes of both individual phases, namely, ferrite and bainite, similarly to the rule of mixtures proposed for composite materials.

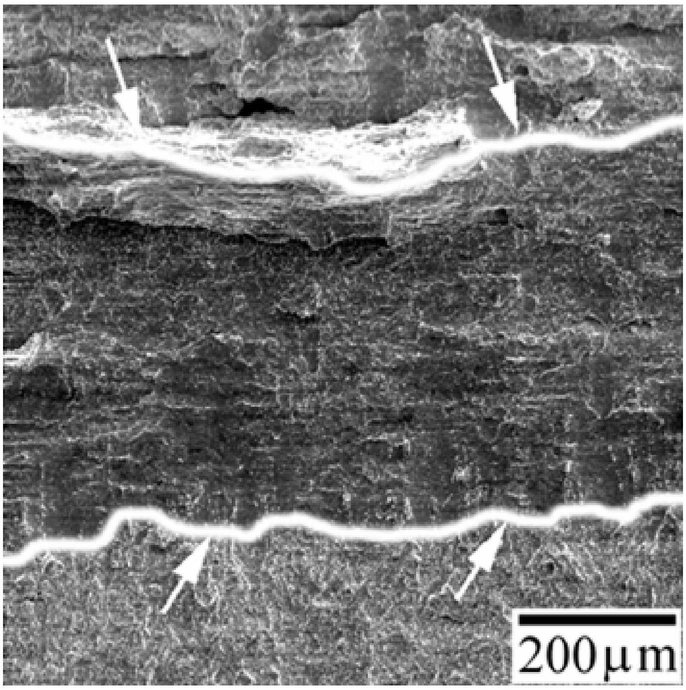
Figure (3) thus confirms the dependence of SZW_C on the grain size as a Hall-Petch relationship (Hall, 1951 & Petch, 1953), given by:

$$SZW_C = b + c \, . \, RCS^{-0.5} \qquad (1)$$

where *b* and *c* are fitting constants.

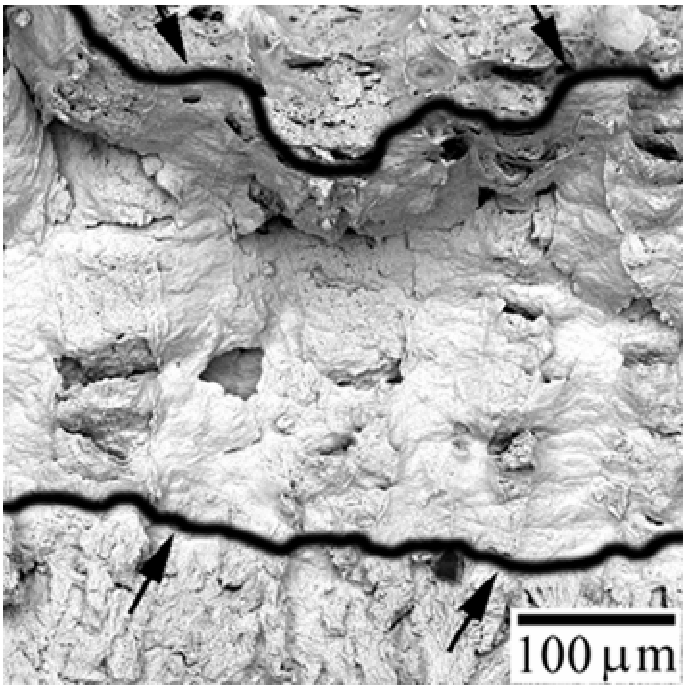


(a)

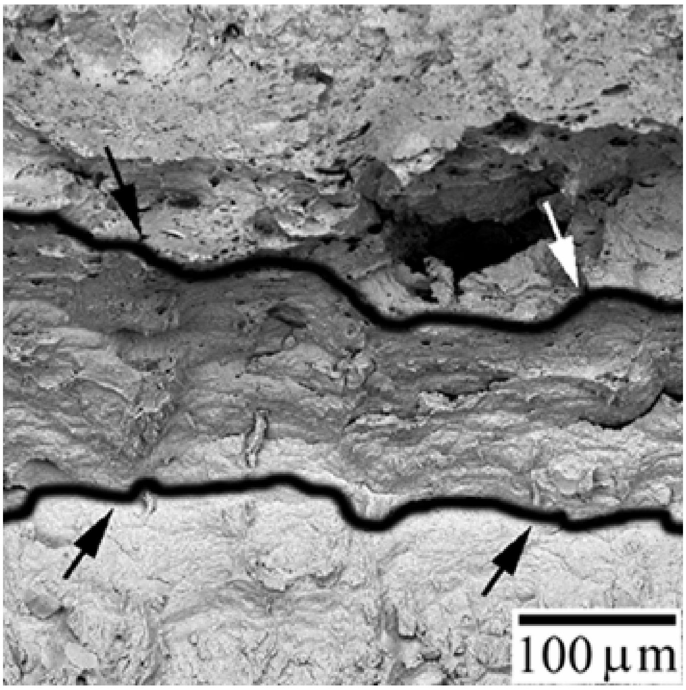


(b)

Figure 1. (a) General view of SZW_C in microstructure A by secondary electron (SE) imaging technique; (b) Detailed view. Beginning and end contours of SZW_C are arrowed. Crack growth is from the bottom to the top of the page.

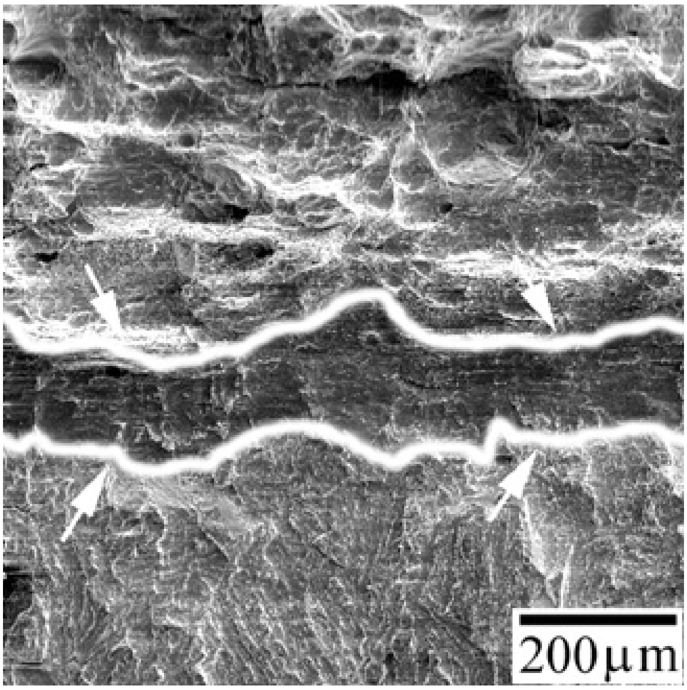


(a)

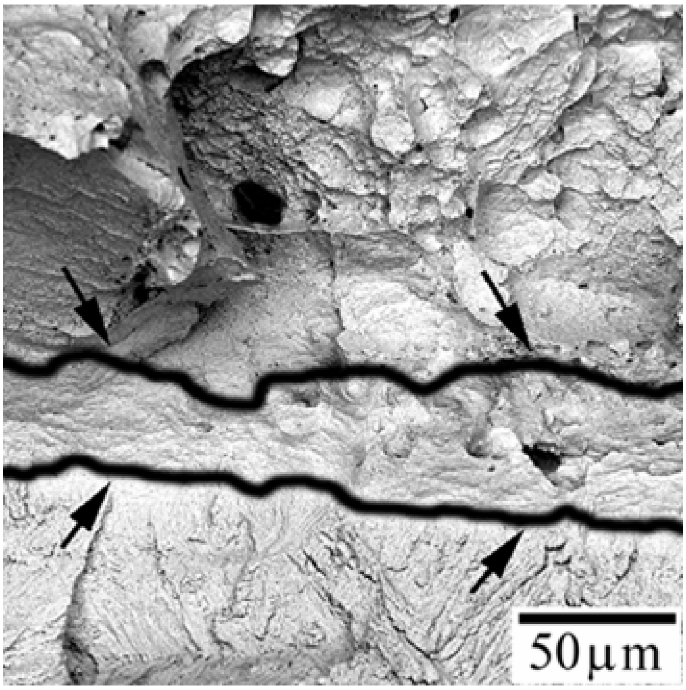


(b)

Figure 2. (*Captioned on the next page*).



(c)



(d)

Figure 2. SEM micrographs of SZW_C in microstructures (a) D by BSE, (b) F by BSE, (c) L by SE, and (d) M by BSE. Beginning and end contours of SZW_C are arrowed. Crack growth is from the bottom to the top of the page.

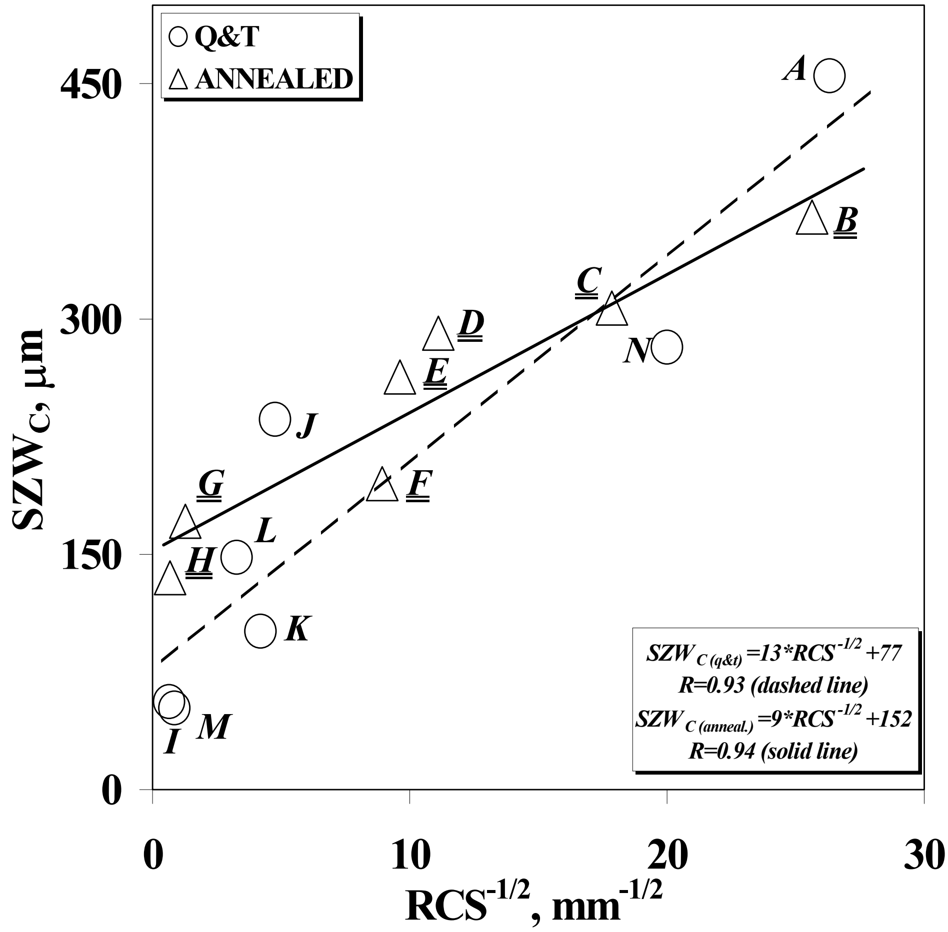


Figure 3. SZW_C vs. RCS for the two classes of microstructures tested.

5. Concluding remarks

The results of an experimental investigation on the physical aspects of the critical stretch zone width (SZW_C) created under dynamic loading conditions have been reported. Charpy impact tests were carried out at ambient temperature in precracked sidegrooved bend bar specimens made of as-received and thermally embrittled conditions of a A508-3A nuclear grade steel.

The initial fracture zone (blunted zone) was examined using scanning electron microscopy (SEM) technique in both secondary (SE) and backscattering (BSE) electron imaging modes. BSE technique has been shown to be superior to SE under some circumstances, so that the use of both image modes is emphasized for the precise definition of the SZW_C contours, whereby one can obtain accurate estimation of this fracture toughness parameter.

Last, but not the least, a Hall-Petch relationship has been disclosed to correlate fairly well the SZW_C values to the representative cell size of both classes of microstructures tested.

6. Acknowledgements

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7. References

[a]Anonymous, 1997, "Standard Test Method for Measurement of Fracture Toughness", Designation ASTM E-1820, Annual Book of ASTM Standards, in CD.

[b]Anonymous, 1997, "Standard Test Methods for Notched Bar Impact Testing of Metallic Materials", Designation E23, Annual Book of ASTM Standards, in CD.

Bassim, M.N., Matthews, J.R. and Hyatt, C.V., 1992, "Evaluation of Fracture Toughness of HSLA80 Steel at High Loading Rates Using Stretch Zone Measurements", Engng Fract. Mech., Vol.43, pp. 297-304.

Broek, D., 1989, "The practical Use of Fracture Mechanics", Kluwer Academic Publishers, printed in the Netherlands.

Hall, E.O, 1951, "The Deformation and Ageing of Mild Steel, Proc. Phys. Soc. B., Vol.64, pp. 747-753.

Hertzberg, R.W., 1991, "Deformation and Fracture Mechanics of Engineering Materials", Third Edition, John Wiley & Sons, printed in the United States of America.

Hyatt, C.V. and Matthews, J.R., 1994, "Variation of Stretch Zone Width with J, Loading Rate, Temperature and Pre-Crack Depth", Int. J. Fract., Vol.66, pp. 19-25.

Petch, N.J., 1953, "The Cleavage Strength of Polycrystals, J. Iron Steel Inst., Vol.174, pp. 25-28.

Pluvinage, G. and Lanvin, A., 1993, "Stretch Zone Geometrical Measurement, a Particular Way to Measure Fracture Toughness", Fatig. Fract. Engng Mater. Struct., Vol.16, pp. 955-963.

[a]Tarpani, J.R., Bose Filho, W.W. and Spinelli, D., 2003, "Hall-Petch Dependence of J-Fracture Toughness Parameters for a RPV Steel - Part I: Annealed Microstructures", Proceedings of the 24th Brazilian Congress of Mechanical Engineering, São Paulo, Brazil.

[b]Tarpani, J.R., Bose Filho, W.W. and Spinelli, D., 2003, "Hall-Petch Dependence of J-Fracture Toughness Parameters for a RPV Steel - Part II: Quenched and Tempered Microstructures", Proceedings of the 24th Brazilian Congress of Mechanical Engineering, São Paulo, Brazil.

[c]Tarpani, J.R., Bose Filho, W.W. and Spinelli, D., 2003, "Hall-Petch Dependence of Dynamic Fracture Toughness for a RPV Steel", Proceedings of the 24th Brazilian Congress of Mechanical Engineering, São Paulo, Brazil.

Zhang, X.P. and Shi, Y.W., 1992, "Constraint of Side-Groove and Its Influence on Fracture Toughness Parameter in Charpy-Size Specimens, Engng Fract. Mech., v.43, pp. 863-867.