HALL-PETCH DEPENDENCE OF DYNAMIC FRACTURE TOUGHNESS FOR A THERMALLY EMBRITTLED RPV STEEL

José Ricardo Tarpani
Materials, Aeronautical and Automotive Engineering Department, Engineering School of São Carlos – University of São Paulo – Brazil
jrpan@sc.usp.br

Waldek Wladimir Bose Filho
Materials, Aeronautical and Automotive Engineering Department, Engineering School of São Carlos – University of São Paulo – Brazil
waldek@sc.usp.br

Dirceu Spinelli
Materials, Aeronautical and Automotive Engineering Department, Engineering School of São Carlos – University of São Paulo – Brazil
dspinell@sc.usp.br

Abstract. *The Charpy impact energies of several microstructures of a reactor pressure vessel steel were assessed on the basis of microstructural parameters. Charpy impact testing were conducted at 300° in a fully automated and instrumented Charpy testing machine using a 300 J energy hammer at an impact velocity of 5.5 m/s. Charpy bend bar specimens (10x10x55mm^3) were machined from thick forged plates (T/4 position, T-L orientation) of the microalloyed steel in the as-received and several thermally embrittled conditions. Similarly to quasi-static fracture toughness results obtained in a parallel study, it has been concluded that the equivalent grain size of dual-phase (ferrite/bainite) annealed microstructures, and the bainite packet size of single-phase quenched and tempered ones control the absorbed energy during impact loading. A Hall-Petch relationship has been ascertained for the dependence of the dynamic fracture energy on the representative cell size of the materials tested. J-integral/Charpy correlations have been derived and shown to hold regardless the J-R curve fitting method applied, namely the widely used power-law, the recently proposed logarithmic fit and the out-dated linear fit method.*

Keywords. *Charpy impact testing, dynamic fracture toughness, Hall-Petch relationship, J-Charpy correlation, RPV steel.*

1. Introduction

In companion papers, Tarpani et all [a,b] (2003) submitted a nuclear grade steel to several heat treatment routes, viz. annealing and quenching and tempering, aimed at obtaining a range of elastic-plastic fracture resistance in the quasi-static loading regimen. Thermal cycles were designed with the goal of simulating the mechanical behavior of structural steels undergoing neutron dose damage in radioactive environments, e.g. reactor pressure vessel (RPV) steels, as suggested by Onizawa et all (1997). In both cases a Hall-Petch relationship applied quite well to the dependence of J-integral fracture toughness parameters on the representative cell size of the microstructures tested.

Since the correlation between Charpy and J-integral testing parameters has been claimed for long by Kussmaul (1983), the above described procedure was reproduced regarding the dynamic performance of the original and thermally embrittled conditions of the RPV steel.

So, the objective of this study is to evaluate the applicability of the Hall-Petch relationship under moderate strain-rate loading conditions as well. For this purpose, precracked, sidegrooved bend bars were impacted in an instrumented Charpy testing machine in order to determine the absorbed net energy during the overall fracture process and relate it to representative cell size of the materials tested.

2. Materials

The Brazilian ASTM A508 Class 3A steel is an exceptionally high-toughness microalloyed RPV material designed for the nuclear industry, exhibiting a Charpy impact energy exceeding 300 Joules when conventional notched bend bar specimens are tested at ambient temperature. The as-received material (named A) has already been fully described by Tarpani et all [a,b] (2003), along with several thermally embrittled products obtained through special heat treatments, which were devised at simulating the mechanical performance of neutron damaged low-alloy steels. Annealed microstructures were denoted B-H, whereas quenching and tempering (Q&T) ones were nominated J, L and N, respectively.

Figure (1) displays the parameterized tensile flow curves till the maximum load capacity of these materials, according to a power-law behavior model, as follows:

$$\sigma/\sigma_y = m \cdot (\varepsilon/\varepsilon_y)^n \quad (1)$$

where σ and ε are true stress and strain, respectively, and *m* e *n* are fitting constants. $\varepsilon_y = \sigma_y/E$, where σ_y is taken at the yield point and E is the Young modulus of the materials tested.

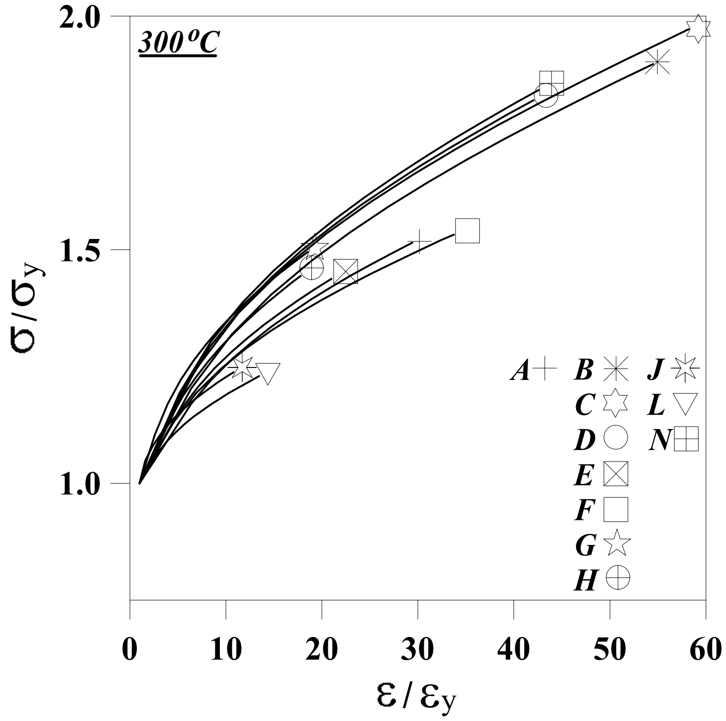


Figure 1. Parameterized power-law stress-strain curves determined according to Eq. (1).

3. Experimental and analytical procedures

Charpy bend bar testpieces (10x10x55 mm^3) were machined in T-L orientation from the one-quarter-thickness position (T/4) of the as-received and heat-treated forged plates. They were fatigue pre-cracked to a nominal 0.5 *a*/W ratio, where *a* is the crack length and W the specimen width, and side-grooved (SG) to 20% and 33% of the specimen gross-thickness, B_G. Special care was taken during the pre-cracking procedure to comply exactly with the requirements established in ASTM standards (1997) related to the maximum stress intensity factor-K developed at crack tip. Charpy specimens were impacted at 300°C in an instrumented testing machine using a 300 Joules hammer travelling at a velocity of 5.5 m/s. The absorbed net energy was digitally recorded, which accounted for energy losses due to friction, windage and specimen tossing. As a general rule, three testpieces were utilized for each testing condition, so that the Charpy energy results provided herein always refer to mean values.

Charpy energies were then tentatively correlated to three J-fracture toughness criteria previously determined by Tarpani et all [a,b] (2003) for the materials tested, namely J_i, J_{50} and $J_D/d\Delta a_{(1mm)}$. It should be emphasized that these J-parameters were derived by applying three distinct J-R fitting methods, namely the widely used power-law, the recently proposed logarithmic fit and the out-dated linear fit method.

4. Results and discussion

Figure (2) displays the relationship between reduction in area, RA, and the inverse of squared root of equivalent grain size, EGS, for dual-phase ferrite/bainite annealed microstructures. This parameter was previously defined by Tarpani et all [a] (2003) as:

$$EGS = ((D_{ferrite}) \,.\, (\%\ Ferrite) + (D_{bainite}) \,.\, (\%\ Bainite))/100 \qquad (2)$$

where $D_{ferrite}$ and $D_{bainite}$ are the ferrite and bainite grain sizes, respectively. Shown in Fig. (2) is also the relationship between RA and tempered bainite packet size, i.e. $1/\sqrt{D_{bainite}}$, of Q&T microstructures, including the as-received condition (A) of the A508 steel. High correlation coefficients for both sets of data points are noticed in this figure.

The notation RCS, representative cell size, adopted by Tarpani et all [b] (2003) denotes the significant cell size of a particular microstructure irrespective if annealed or Q&T materials. In this regard, RCS equals the equivalent grain size for dual-phase ferrite/bainite annealed products, whereas RCS is the tempered bainite packet size for single-phase Q&T microstructures.

As seen for both classes of microstructures in Fig. (2), RA and RCS values obey a Hall-Petch dependence (Hall, 1951 & Petch, 1953), given by:

$$RA = b + c \cdot RCS^{-0.5} \quad (3)$$

where b and c are fitting constants.

This relationship indicates that RA is grain size driven for both annealed and Q&T microstructures. Later in this paper, the same dependence will be shown regarding their Charpy impact energies.

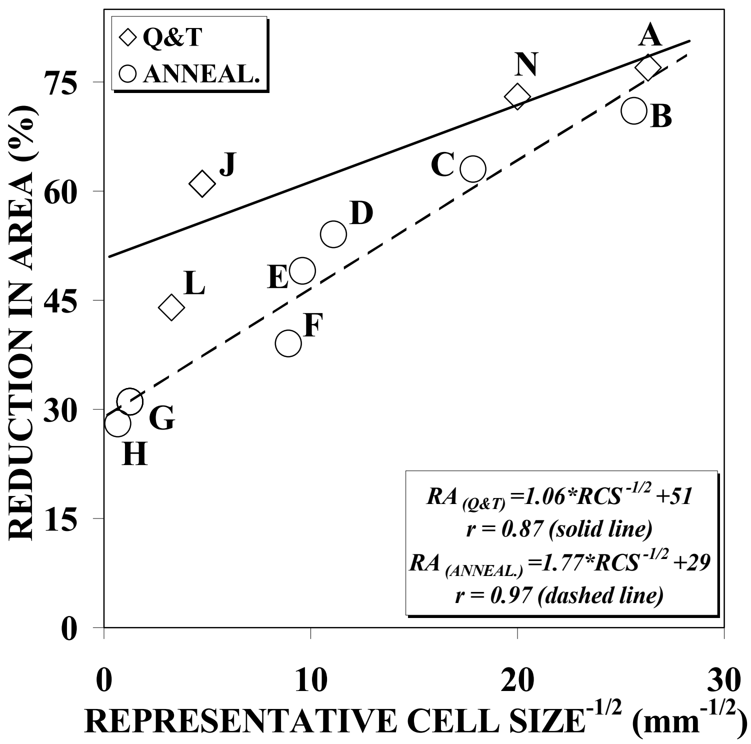


Figure 2. Hall-Petch dependence of RA on RCS, according to Eq. (3).

In Figure (3), the net Charpy impact energy, CIE, dependence on RCS is also shown according a Hall-Petch relationship in the format:

$$CIE = d + e \cdot RCS^{-0.5} \quad (4)$$

where d and e are fitting constants.

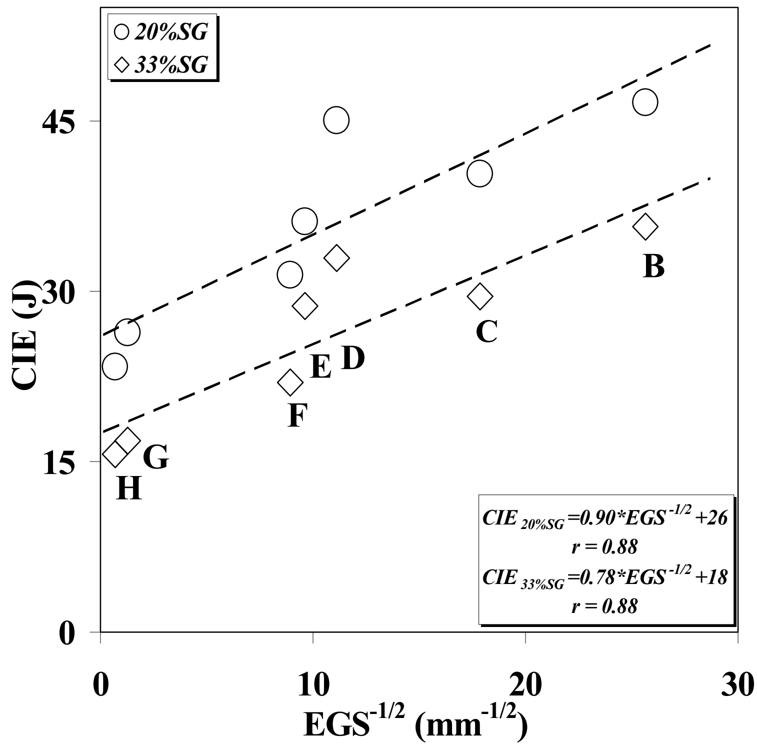
Figure (3a) shows an unexpected behavior of microstructure D on the basis of the EGS concept, in which the dynamic fracture energy should increase with decreasing grain size. It can be observed that this microstructure, despite being coarser than C, presents a significantly better dynamic performance than the latter. This behavior was previously verified by Tarpani et all [a] (2003) under quasi-static loading regimen, and it was explained in terms of the predominant role played by the bainite phase refinement over the equivalent grain size concept, as long as they are competitive mechanisms affecting the mechanical behavior of annealed microstructures. The same assumption can be postulated for higher strain-rate conditions as imposed in the present study.

It is worthy of note in Figs. (2) and (3b) that, given a fixed RCS value, Q&T microstructures perform much better than annealed ones. Fig. (3) also confirms that deeper side-grooving the Charpy impact test specimen has a pronounced effect on fracture toughness results, with conservative values being generated.

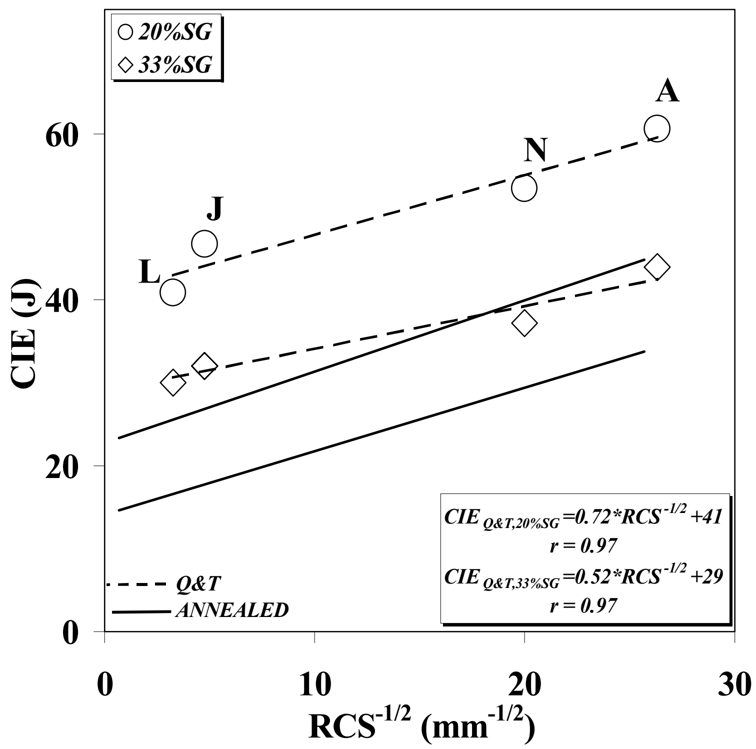
Figure (4) plots Charpy energy of annealed materials versus respectively J_i, J_{50} and $J_D/d\Delta a_{(1mm)}$ criteria, which have been derived by Tarpani et all [a,b] (2003) in a parallel study. Very good data correlation is noticed for 33%SG test specimens, and the same can be observed in Fig. (5) for Q&T microstructures. These results support and strengthen the so-desired compatibility between quasi-static and dynamic fracture toughness indexes, as originally claimed by Kussmaul (1983). Notice that only lower and upper contours of 20%SG results are furnished in Figs. (4) and (5) for the materials tested.

Figures (4) and (5) unequivocally depict the conservative aspect of the logarithmic fit of J-Δa data points in generating lower J_i and J_{50} values, as compared to conventional power-law and mainly the old-fashioned linear data fitting. Observe that this conclusion does not apply to the $dJ_D/d\Delta a_{(1mm)}$ criterion. In fact, an inverted behavior is noticed regarding the latter fracture-toughness parameter.

Correlation between quasi-static elastic plastic fracture mechanics properties and grain size has rarely been proposed in literature, Srinivas et all (1987, 1991), invariably on the basis of the widely accepted Hall-Petch relationship and for single-phase metallic materials only. The present study has shown the potential of applicability of such an approach regarding a broad range of grain size in single- and dual-phase microstructures of a structural nuclear grade steel, when the net absorbed energy under impact loading regimen is the chief concern.



(a)



(b)

Figure 3. Hall-Petch dependence of CIE on RCS (or EGS), according to Eq. (4). (a) Annealed; (b) Q&T microstructures. In (b), results from annealed materials are drawn as baseline.

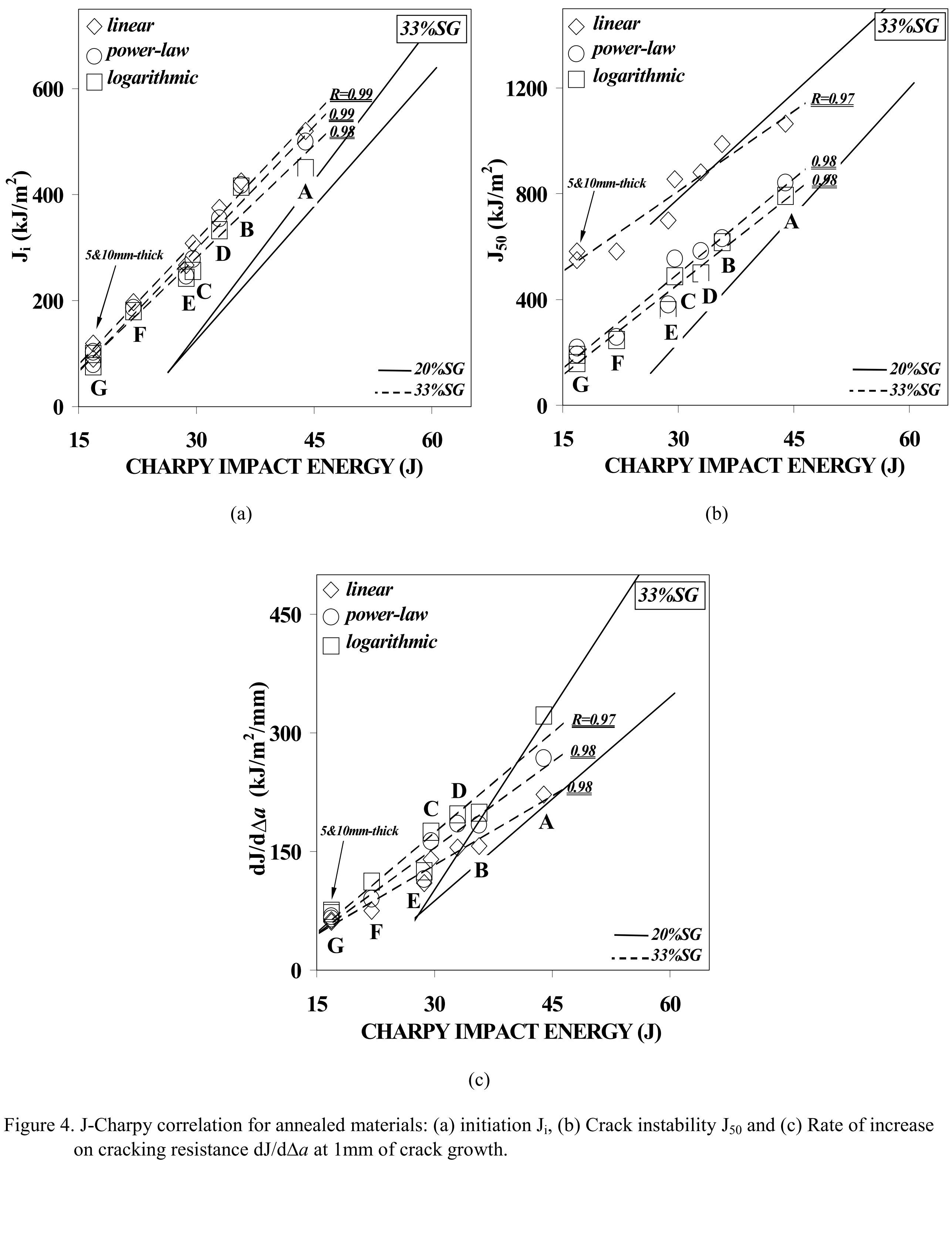
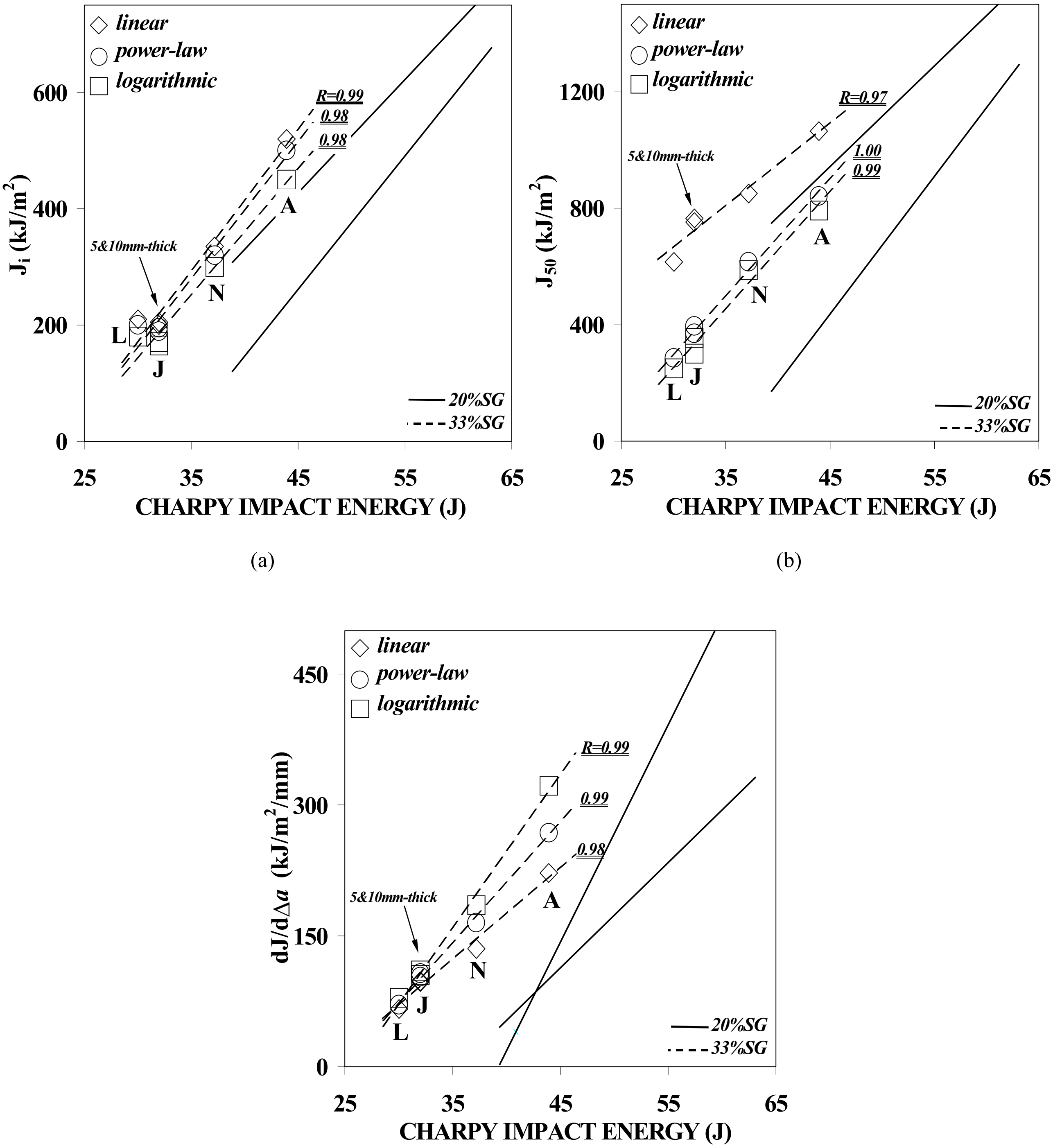


Figure 4. J-Charpy correlation for annealed materials: (a) initiation J_i, (b) Crack instability J_{50} and (c) Rate of increase on cracking resistance $dJ/d\Delta a$ at 1mm of crack growth.



(a) (b) (c)

Figure 5. J-Charpy correlation for Q&T materials: (a) initiation J_i, (b) Crack instability J_{50} and (c) Rate of increase on cracking resistance dJ/dΔa at 1mm of crack growth.

5. Concluding remarks

The elastic-plastic crack extension behavior under dynamic loading condition of single- and dual-phase microstructures of a low alloy RPV steel has been assessed on the basis of microstructural parameters.

It has been concluded that the equivalent grain size of dual-phase ferrite/bainite annealed microstructures and the tempered bainite packet size of single-phase Q&T microstructures do control the energy absorption capacity of materials during overall fracture processes.

A Hall-Petch relationship has been found to correlate the impact energy to the representative cell size of the microstructures tested. As a consequence, a straightforward correlation can be inferred between Charpy impact energy and several J-fracture toughness parameters of the nuclear power industry, as often postulated in literature.

As a matter of fact, very promising J-Charpy correlations have been derived in this study and shown to hold regardless the J-R curve fitting method used.

6. Acknowledgment

The authors gratefully acknowledge the financial support provided by FAPESP (contracts 97-05652/1 and 99/09431-5).

7. References

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

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

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

Kussmaul, K., 1983, "West German Research Programs on Irradiation Effects on Reactor Pressure Vessels", ASTM STP (Special Technical Publication) 819, pp. 16-28.

Onizawa, K. and Suzuki, M., 1997, "Correlation Among the Changes in Mechanical Properties due to Neutron Irradiation for Pressure Vessel Steels", ISIJ Int., Vol.37, pp. 821-828.

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

Srinivas, M., Malakondaiah, G., Armstrong, R.W. and Rao, P.R., 1991, "Ductile Fracture Toughness of Polycrystalline Armco Iron of Varying Grain Size", Acta Metall. Mater., Vol.39, pp. 807-816.

Srinivas, M., Malakondaiah, G., Armstrong, R.W. and Rao, P.R., 1987, "Influence of Polycrystal Grain Size on Fracture Toughness of and Fatigue Threshold in Armco Iron", Engng Fract. Mech., Vol.28, pp. 561-576.

[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.