ON THE DEVELOPMENT OF A RELATIONSHIP BETWEEN FRACTAL DIMENSION AND IMPACT TOUGHNESS

O.A.HILDERS [1],N.D.PEÑA [1],D.PIL0 [2] & C.SUAREZ [3]

[1] Escuela de Ingeniería Metalúrgica y Ciencias de los Materiales, Universidad Central de Venezuela, Apartado 47514 Caracas, 1041-A, Venezuela.

[2] Departamento de Ingeniería Mecánica, Universidad Simón Bolívar, Apartado 80659, Caracas, Venezuela.

[3] Escuela de Ingeniería Mecánica, Universidad del Zulia, Apartado 10482, Maracaibo, 4002-A, Venezuela.

ABSTRACT

V-notch Charpy samples of a commercial medium-carbon ferrite-pearlite steel rolled (10% and 25%) at 25, 200, 500 and 700 ºC, wern tested at room temperature to determine fractal dimensions, D_f, of the fracture surfaces. The fractal dimensional increment, D_f', as measured by the slit island technique and the impact toughness, KCV, showed a positive relationship, contrary to some previous results. This discrepancy could be explained from the basic features of the different fracture micromechanisms, wich involve a pattern of discrete fractographic structural units, different in size for each case, related to the energy absorption during the fracture process.

Keywords: Fractal slit island technique, impact toughness, fracture micromechanisms, fractography.

DESARROLLO DE UNA RELACIÓN ENTRE LA DIMENSIÓN FRACTAL Y LA TENACIDAD DE IMPACTO

RESUMEN

Una serie de probetas de impacto Charpy de acero de medio carbono (microestructura: ferrita/perlita) laminadas (10% y 25%) a 25, 200, 500 y 700 ºC fueron ensayadas a temperatura ambiente, determinándose la dimensión fractal, D_f , de las superficies de fractura. El incremento en dimensión fractal, D_f' , encontrado a través del método de las secciones finas, y la tenacidad de impacto, KCV, mostraron una relación directa, contraria a algunos resultados anteriores. Esta discrepancia podría explicarse a partir de los aspectos básicos de los diferentes micromecanismos de fractura, los cuales implican un patrón de pequeñas unidades estructurales de diferente tamaño en cada caso, relacionadas con la absorción de energía durante el proceso de fractura.

Palabras clave: Dimensión fractal, método de las secciones finas, tenacidad de impacto, micromecanismos de fractura, fractografía

INTRODUCTION

Materials science is one of the fields in which quantitative fractography is being used (COSTER & CHERMANT, 1983; UNDERWOOD & BANERJI, 1986; PANDE *et al.*, 1987; HILDERS & SANTANA, 1988; EL-SOUDANI, 1990; KRUPIN & KISELEV, 1991, TANAKA, 1993; NAGAHAMA, 1994). Particularly, fracture is currently studied by fractal geometry in an attempt to develop complementary correlations between microstructure and fracture mechanics (MANDELBROT *et al.*, 1984, ROSENFIELD, 1987; WOJNAR & KUMOSA, 1990; DING *et al.*, 1994).. Since qualitative fractography is unable to distinguish fracture surfaces with very similar features, the fractal characterization becomes an increasingly important method in fractography.

In spite of this regard, some aspects related with the methods to determine the fractal dimension are still open to discussion. Quite recently, Pande (PANDE *et al.*, 1987) criticized the slit island analysis suggested by Mandelbrot (MANDELBROT *et al.*, 1984), to obtain the fractal dimension, based on the assumption that the island shape (the ratio of length to breadth) must be an invariant with size, and on the difficulty related with the connection between the roughness exhibited by an island contour and the roughness of the fracture surface. They found a negative correlation between fractal dimension and the dynamic tear energy in a series of titanium alloys with varying amount of Zr, as Mandelbrot (MANDELBROT *et al.*, 1984), who studied the fracture surfaces of 300 grade maraging steel and correlated the fractal dimensional increment with the impact energy. On the other hand, Ray and Mandal (RAY & MANDAL, 1992) critically analized the results of Pande (PANDE *et al.*,1987), and showed that the slit island method is essentially correct. The material studied in this case, was a structural HSLA steel of commercial grade, but the values of fractal dimension bear a positive linear correlation with impact energy. as measured by standard Charpy impact test. Other results have been shown (LUNG & ZHANG, 1989) that the values of fractal dimension decrease linearly with an increase (FAHMY *et al.*, 1991) of the logarithm values of fracture toughness K_{IC}.

It is obvious that since the fracture phenomenon is very complicated, (a great variety of mechanisms have to be taken into account) it is not an easy task to develop a complete theory which satisfactorily explain the apparent trends experimentally observed for different alloys systems. In the present paper we deal with the examination of the fracture process of a commercial medium-carbon ferrite-pearlite steel, in order to define the relationship between the impact energy and the fractal dimension, as measured by the slit island technique. Ordinary structure-property relationships have been very well described for ferrite-pearlite structures (BURNS & PICKERING, 1964; GLADMAN *et al.*, 1972; CIIEN & WANG, 1994), which provide a sound basis to the study of the fracture process by the fractal analysis aproach.

EXPERIMENT AL TECHNIQUES

Material and Thermomechanical Treatments

The material used in this investigation was received as 130 kg heat with a chemical composition (wt%) of 0.48 C, 0.52 Mn, 0.25 Si, 0.03P and 0.019 S. The steel was normalized after a complete austenitization treatment at 800 ºC. Prior to heat treatment, the microstructure consisted of some areas of polygonal ferrite, grain boundary networks of ferrite and pearlite nodules. The heat was split cast into six ingots which were homogenized at 1000 ºC, hot rolled in several passes to plates 14.5 mm thick and air cooled to room temperature. In order to ensure a variety of ferrite-pearlite microstructures reflecting different toughness behavior, the plates were rolled at temperatures ranged between 25 ºC and 700 ºC for different amounts of reduction (see Table 1).

Mechanical Testing

For each treatment condition, ten standard V-notch Charpy specimen were prepared. The notched face was perpendicular to the rolling plane, and the blow was administered parallel to this face. Impact testing was carried out at room temperature, taking the absorbed energy and the macroscopic fracture appearance for the total sixty samples. Further fracture examination was performed using a scanning electron microscope operated at 25 kv.

Since the main object of this work was to relate, as accuratelly as possible, the impact toughness to the fractal dimension, the three samples with the closest values of toughness respect to the average (over the total samples for each condition), were selected for the application of the slit island technique, being the reported value of impact toughness for each treatment, the average of these three values (see Table 2).

Fractal Dimension Measurements

The fractal dimension D_f is defined as:

$$L = Lo(\eta)^{-(D_f - D)} \qquad (1)$$

where L is the measured length, area etc., η is the measuring unit, Lo, is a constant and D is the topological dimension. For a rough surface, $D_f > 2$ (being D = 2), so that $L \to \infty$ as $\eta \to 0$. From equation (1), the fractal dimensional increment can be written as:

$$D_f' = D_f - D = -\frac{d(\log L)}{d(\log \eta)} \qquad (2)$$

Following the analysis of Mandelbrot (MANDELBROT *et al.*, 1984), when island are derived from an initial fractal surface, their coastlines are of fractal dimensional increment $D_f' = D_f - D = D_f - 1$. For slit is land analysis D_f' can be evaluated from the slope of the curve defined by $\log\sum A_i$ vs $\log\sum P_i$,where A_i and P_i are the area and the perimeter respectively of the ith island on a particular jth layer containing n such islands, so D_f' is defined as:

$$D_f'' = \frac{d\left(\log \sum_{i=1}^{n} A_i\right)}{d\left(\log \sum_{i=1}^{n} P_i\right)} - 1 \qquad (3)$$

The fractured specimens were mounted in rcsin and polished in stages, being each stage represented by a jth layer. $\sum A_i$ and $\sum P_i$ were evaluated using an image analyzer and an optical microscope.

RESULTS AND DISCUSSION

From normal experience, it can be expected a positive relationship between fractal dimension and impact toughness, which agree with the results obtained in the present work (see Figs. 2 and 3). In general, there is an intimate relationship between toughness and the capacity for plastic deformation, in the sense that materials showing great plasticity also have a high toughness. On the other hand, low toughne:ss materials show a brittle behavior and lower plastic deformation. Theoretically, a high fractal number is supposed to be characteristic of a rough surfaces, which in turn must be associated to a higher plasticity. The lower limit for the fractal dimensional increment (D_f' =O) has to be related to a totally flat fracture surface.

The results of this investigation tend to support the concept of a pattern of discrete fractographic steps or structural units, related to the energy absorption during the fracture process. The material with a greater tendency to brittle fracture, showed the largest fractographic structural unit, thus, a decreasing in these units might increase the toughness. This structural unit can be associated with the cleavage facets, which lay nearly parallel to the mean plane of fracture for the highly brittle condition. As the toughness increases, the angle between the cleavage facets an the local mean plane of fracture increases. This phenomenon, naturally, introduces a greater degree of roughness, which can be readily detectable with reasonable accuracy. Fig.1 represents this transition, from the material deformed 25% at room temperature, to the material deformed 10% at 700·ºC (Figs. 1-a and 1-g respectively). Although all the fractographs in Fig.l show a mixed mode of decohesion with a strong predominancy of cleavage and/or quasi-cleavage, for the tough samples (material deformed 10% at 200 ºC; Fig. 1-e and material deformed 10% at 700 ºC; Fig. 1-g) it can be seen a slightly increase in the microvoid growth to coalescence mechanism component, together with a decrease in the cleavage facet size, an increase in the angle between the facets and the local mean plane of fracture and an increase in the size of the dimples. This later feature can be detected from the details showed in Fig 1-b; 1-d; 1-f and 1-h, which represent the evolution of the dimple size in the small areas of the main fractographs corresponding to the matedal tested from the less to the more tough condition. The described behavior leads to the impact toughness-fractal dimension relationship depicted in Fig.3.

For the ferrite-pearlite steel, the fractal dimensional increment is seen to increase monotonically with impact toughness, being the slope of the curve constant to about 19.81 J, where D_f' suddently increases from 0.40 to 0.83. A similar positive relationship was obtained by Ray (RA Y & MANDAI., 1992), which is shown in the same figure. On the other hand, although Mandelbrot (MANDELBROT *et al.*, 1984) did not show any fractographic evidence of the fracture micromechanism for the heat-treated 300 grade maraging steel, their results suggested that the failure of the samples occurred mainly by dimple separation. In contrast to our results, and those of Ray (RAY & MANDAL, 1992) the relationship between the impact toughness and Dt, is a negative one. The later apparent discrepancy could be simply explained from the basic differences between the fracture micromechanisms, i.e. the process of energy absorption is different for different·fracture micromechanisms, which means that the roughness of a fracture surface is not necessarily related with the toughness in a positive manner.

We can consider a first stage in the development of a relationship between the impact toughness and the fractal dimension, in which D_f' increases as the toughness increases, being cleavage the main fracture mode. It is supposed that a transition in the fracture micromechanism is posible, provided a change in the microstructure is allowed. Just before appreciable plastic relaxation starts to occur locally, D_f'reaches a maximium value and cleavage facets develop in a ridge and abrupt valley manner, i.e. forming a relatively high angles with the mean plane of fracture. At this point, the microvoid coalescence micromechanism component is very small. A second stage can start now, when the lowering of the stress prevents the achievement of the local critical stress intensity for cleavage and tiny microcracks distort into a voids that grow and eventually link, generating a less rough surface of normal tear and/or shear type, even when the absorbed energy were greater. The higher the microvoid coalescence micromechanism component, the lower the surface roughness and the higher the energy absorbed, so that in this second stage, D_f' decreases as the toughness increases. It must be realized that, on a local scale, a fracture surface of say, shear type, consists of sections on a number of nearly parallel planes, so that the fracture path can move leaving an elongated parabolic dimples which introduce a lower surface relief (HILDERS, 1993). On the other hand, for both, tear and shear rupture modes, the deep of the dimples is a fraction of the grain size, unlike the cleavage facets, which can encompass an entire grain. In the present work only the first stage was developed, as in the case of Ray (RAY & MANDAL, 1992), and from the work of Mandelbrot (MANDELBROT *et al.*, 1984), probably just the second stage was observed.

CONCLUSIONS

Contrary to some previous results, the fractal dimensional increment, D_f', as measured by the slit island technique and the impact toughness, KCV developed a positive relationship in a commercial medium-carbon ferrite-pearlite steel. Two stage fracture micromechanism can be envisaged, in wich the first one involves an increase in D_f' as the impact toughness increases, being the cleavage facets the microstructural units responsible for the roughness of the fracture surface. In the second stage, the microvoid coalescence micromechanism component increases as the change in the microstructure is allowed, generating a less rough surface, so D_f' decreases as the toughness increases.

In the present work, just the first stage was observed and the values of D_f' increase linearly with impact toughness, from nearly 0.04 to 0.40, where an abrupt departure is observed until the value of 0.83, with a corresponding increase in toughness. It is apparent from the above. that the fracture micromechanisms can play a key role in the correct interpretation of the relationship between the fractal dimensional increment, as a measure of fracture roughness, and sorne important properties of metal alloys, like toughness.

ACKNOWLEDGMENTS

The authors would especially like to thank Dr. M. Ogura, of the Centro de Microscopía Electrónica, Facultad de Ciencias, UCV, for his advice and the use of the scanning electron microscope. This work was partially supported by the Consejo de Desarrollo Científico y Humanístico ofthe UCV.

REFERENCES

Coster M. & J.L. Chermant. 1983. Recent developments in quantitative fractography. Int. Met. Rev., 28: 228-250.

Underwood E.E & K. Banerji. 1986. Fractals in fractography. Mat. Sc. Eng., 80: 1-14.

Pande C.S., L.E. Richards, N. Louat, B.O. Dempsey & A.J. S,Chwoeble. 1987. Fractal characterization of fractured surfaces. Acta Metall., 35: 1633-1637.

Hilders O.A. & M.G. Santana. 1988. Toughness and fractography of austenitic type 304 stainless steel with sensitization treatments at 973 K. Metallography, 21: 151-164.

El-Soudani S.M. 1990. Quantitative fractography and fracture mechanics characterization. J. Min. Met. Mat. Soc., 42: 20-27.

Krupin Y .A. & I.K. Kiselev. 1991. On correctness of statistical determination of the fractal dimension using the slit island method and fractal properties of the basic fracture surfaces. Scripta Metall. et Mater., 25: 655-658.

Tanaka M. 1993. Effects of microstructures and creep conditions on the fractal dimension of grain- boundary fracture in high temperature creep of heat- resistant alloys. Zeitzch. Metallk., 84: 697-701.

Nagahama H. 1994. A fractal criterion for ductile and brittle-fracture. J. App. Phys., 75: 3220-3222.

Mandelbrot B.B., O.E. Passoja & A.J. Paullay. 1984. Fractal character of fracture surfaces of metals Nature, 308: 721-722.

Rosenfield A.R. 1987. Fractal mechanics. Scripta Metall., 21: 1359-1361.

Wojnar L. & M. Kumosa. 1990. Advanced quantitative analysis of fracture surfaces. Mat. Sc. Eng., A128: 45-53.

Ding H.Z., X.S. Xing & H.S. Zhu. 1994. Fractal behavior in fatigue of materials. J. Mat. Sc. Lett., 13: 636-638.

Ray K.K. & G. Mandal. 1992. Study of correlation between fractal dimension and impact energy in a high strength low alloy steel. Acta Metall. Mater., 40: 463-469.

Lung C.W. & S.Z. Zhang. 1989. Fractal dimension of the fractured surface of materials. Physica D, 38: 242-245.

Fahmy Y., J.C. Russ & C.C. Koch. 1991. Application of fractal geometry measurements to thc cvaluation of fracture toughness of brittle intcrmetallics. J. Mater. Res., 6: 1856-1861.

Burns K.W. & F.B. Pickering. 1964. Dcformation and fracture of ferrite-pearlite structures. J. Iron Steel lnst., 185: 889-906.

Gladman T., L.D. Mcivor & F.B. Pickering. 1972. Sorne aspects of the structure-property relationships in high-carbon ferrite-pcarlitc steels. J. Iron Steel lnst., 210: 916-930.

Chen J.H. & G.Z. Wang. 1994. Micromcchanism of the transition of fibrous cracking to cleavage of C- Mn base and weld steel. Met. and Mat. Trans., 25A: 1381-1390.

Hilders O.A. 1992. Fracture path profilomctric analysis, fracture toughness and mechanical properties in sensitized 304 stainless stecl. Proc. Applications of stainless steel 92, Vol. 2, H. NORDBERG & J. BJÓRKLUND Eds., Jemkontoret, Stockholm, p. 1017.

- - , D. Pilo, M. Ogura & A.E. Mora. 1993. Stereology of dimple fracture and mechanical properties correlations in an austenitic alloy with few inclusions. Acta Mic., 2:15-27.

LIST OF SYMBOLS

A_i	Area of the *i*th island on a particular *j*th metallographic layer, in the slit island method. (μm²).
D	Topological Dimension (0, 1, 2, 3).
D_f	Fractal Dimension.
D_f'	Fractal Dimensional Increment.
K_{IC}	Fracture Toughness. (MPa√m).
L	Measured Length, Area etc. (μm), (μm²) etc.
L_o	Constant (equation 1).
Pi	Perimeter of the ith island on a particular jth metallographic layer, in the slit island method. (μm).
η	Measuring Unit. (μm), (μm²) etc.

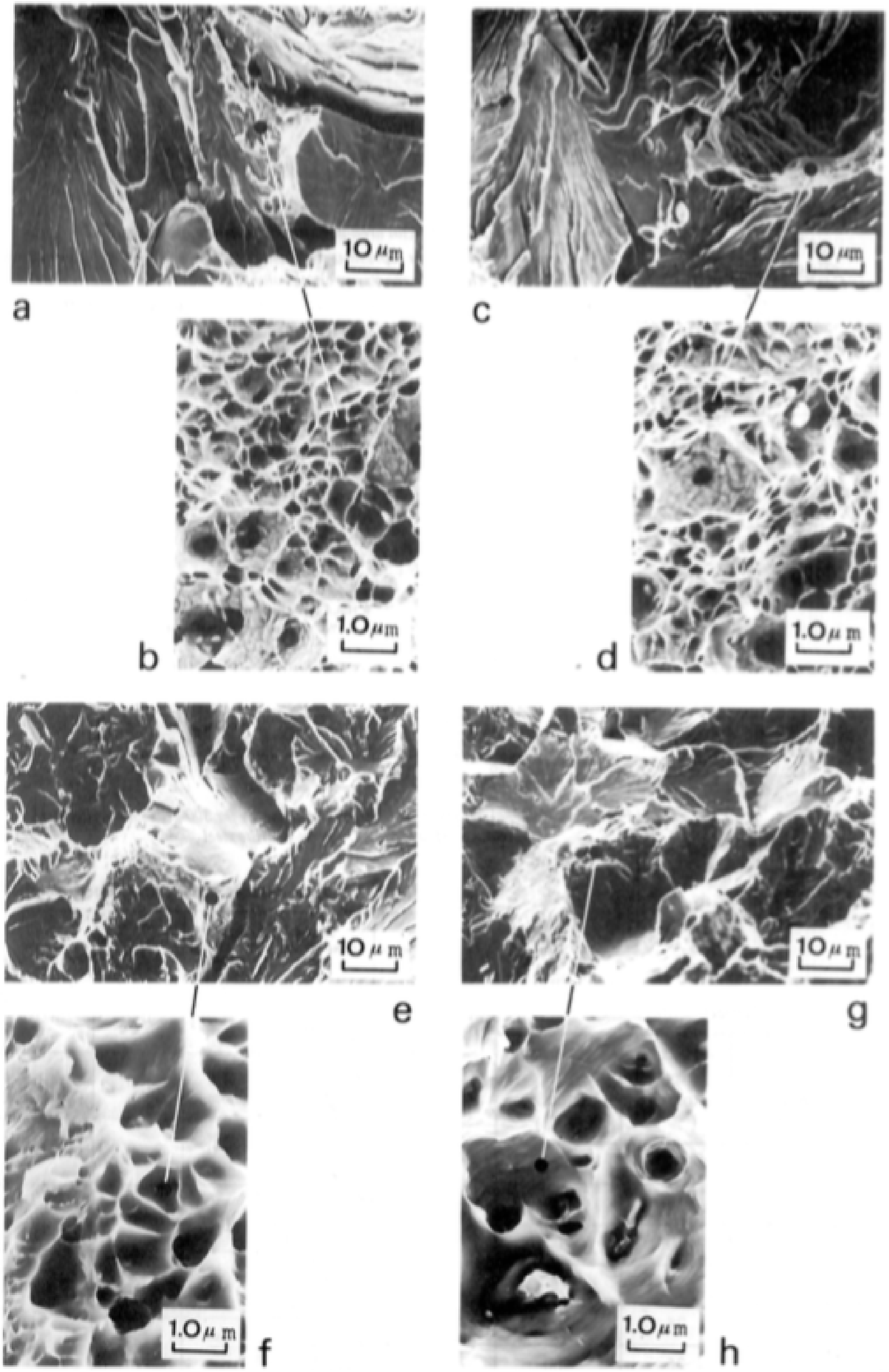

Figure l. *Scanning electron fractographs of Charpy samples broken at room temperature, showing the changes in the surface relief (a) 25% reduced by rolling at 200 ºC, (e) 10% reduced by rolling at 200 ºC, (g) 10% reduced by rolling at 700 ºC. (b), (d), (f) and (h) represent the evolution of the corresponding dimple size.*

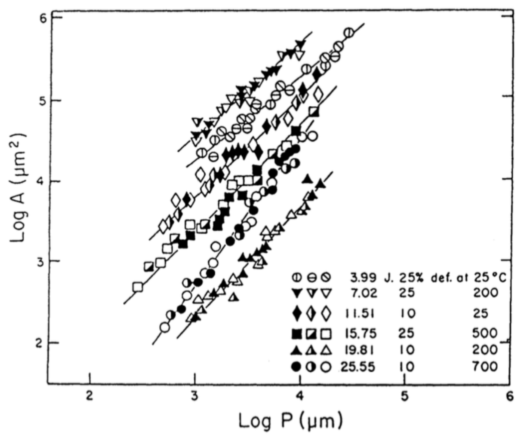

Figure 2. *Fractal area-perimeter relationship for slit islands. Each curve represents the average of three Charpy impact specimens. The corresponding average value o f the absorbed energy for each experimental condition is shown in the figure.*

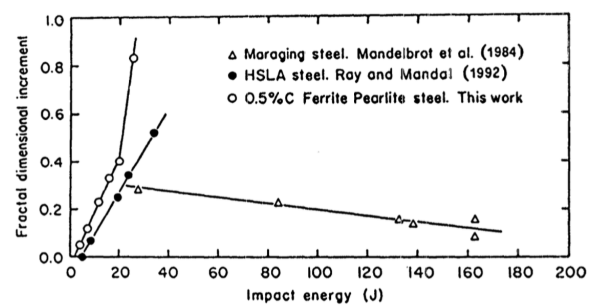

Figure 3. *Fractal dimensional increment vs Charpy impact energy for 300 grade maraging steel, HSLA steel and 0.5%C ferrite-pearlite steel*

Table 1. Experimental Data

Treatment	Number of Samples Tested	Reduction by Rolling (%)	Temperature of Reduction (°C)
A_1	10	10	25
A_2	10	10	200
A_3	10	10	700
B_1	10	25	25
B_2	10	25	200
B_3	10	25	500

Table 2. Impact Energy Values and Fractography

Treatment	Fracture Appearance and Mode	KCV (J) for Selected Samples	Reported Average Values of KCV (J)	KCV (J) Averaged Over 10 Samples
A_1	very flat, shiny 90% cleavage 10% quasi-cleavage and dimpled areas	11.25 12.38 10.90	11.51	12.15
A_2	irregular, grey 45% cleavage 50% quasi-cleavage 5% dimpled areas	20.96 18.27 20.20	19.81	18.91
A_3	irregular, grey 35% cleavage 60% quasi-cleavage 5% dimpled areas	26.89 25.43 24.33	25.55	23.34
B_1	very flat, shiny 95% cleavage 5% quasi-cleavage and dimpled areas	4.25 3.49 4.23	3.99	3.90
B_2	very flat, shiny 95% cleavage 5% quasi-cleavage and dimpled areas	6.41 8.24 6.41	7.02	7.92
B_3	irregular, shiny 90% cleavage 10% quasi-cleavage and dimpled areas	15.00 16.29 15.96	15.75	16.09