INFLUENCE OF THE SAMPLE THICKNESS ON THE ESSENTIAL SPECIFIC WORK OF FRACTURE

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ABSTRACT

In the fracture of ductile materials, the classical parameters of fracture toughness such as the critical intensity stress factor have not validity. Only under special restrictions, the parameter J may be valid. For this reason, it is necessary to define a new quantity, the essential specific work of fracture w_e, which value is possible to demonstrate that depends on the thickness of the material. This dependence is not apparent although it is important not only by a scientific concern but also by the industrial requirement to determine this parameter in a fast and secure manner. In the present work, the results of the essential specific work of fracture measured for a steel sheet of thickness varying from 180 to 900 μm produced by the local industry are showed. The recommendation of the ESIS 1995 Protocol has been used for the determination of the essential specific work of fracture. An enhancement in the approximation of the relation between essential specific work of fracture and the material thickness has been done, concluding that a linear relation between both parameters seems to exist at least in the range of thicknesses studied. Furthermore, in spite of the experimental complexity involved in the computation of J, the essential specific work of fracture is the most appropriate parameter for the fast evaluation of the fracture response of ductile materials.

INTRODUCTION

The principal tonnage of steel actually produced in the world corresponds to carbon steel, the low-carbon steel being the most important of them, owing to three principal applications: the can industry, architectonic uses (wall, roof, profiles) and car components (bonnet, roof, wings). In the first case, cans may be used as paints containers, fuel and oil vessels, for the food and beverage industries.

The toughness dependence on thickness can be observed schematically in fig.1. The value of toughness is a constant, independent of the thickness of the material and hence, a material property, for thicknesses greater than a critical value, called B_c. For thicknesses lower than this critical value, toughness increases up to a maximum corresponding to thickness B_0 and then decreases again for very small thicknesses. This behaviour is related to the gradual transition from the full-plane-strain to the full-plane-stress states. For a small thickness a plane-stress condition prevails, and the plasticity around a crack is important. This fact produces the increment of the toughness observed in fig. 1 for thicknesses lower than B_c. For the plane-strain condition, the plasticity around the tip of the crack decreases. In this case, the toughness also decreases and becomes a material property.

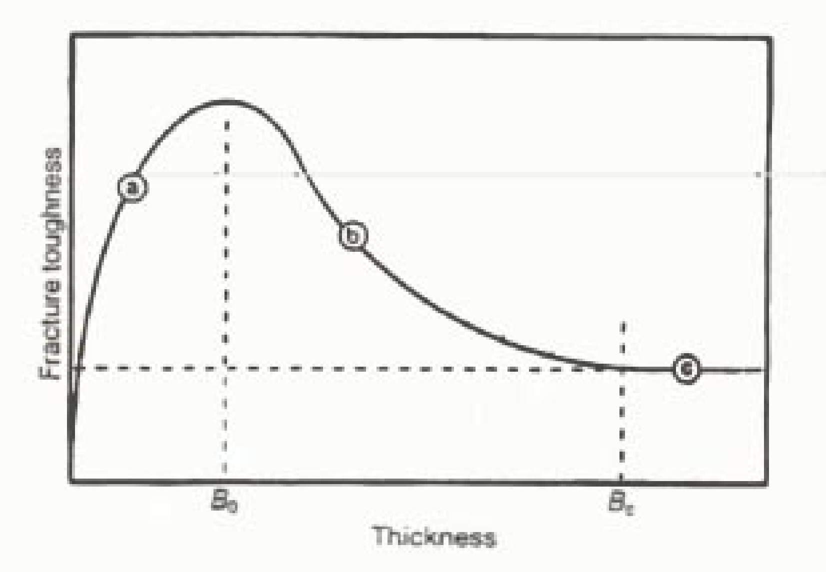

Figure 1. - Toughness as a function of thickness.

The critical thickness B_c may be determined from the following equation [1,2]:

$$B_c = 2.5\left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2 \tag{1}$$

where K_{IC} corresponds to the plane-strain toughness, independent of the thickness and σ_{ys} is the tensile yield stress of the material. For thicknesses below B_0, different tendencies of toughness have been observed.

In this work, the dependence between toughness and thickness under a plane-stress state is studied, for two different low carbon steels. To this end, the concept of specific essential work of fracture, proposed by Broberg [3], is applied and thus replacing the toughness for very ductile materials under plane stress condition. If a fracture process is considered, the non-elastic zone near the crack can be separated in the process zone, where the fracture takes place and the outer plastic zone, where plastic strain occurs, see figure 2. Hence, it can be concluded that the total work of fracture is the sum of the essential work occurring in the process zone plus the non-essential work, corresponding to the outer plastic zone. The former is directly related to the energy required to produce two new surfaces of a fractured material and it is called the essential work of fracture W_e. The second is the work related to the plastic deformation around the crack and it is called the non-essential plastic work, W_p. The total work of fracture, W_f can be expressed then as [3]:

$$W_f = W_e + W_p \tag{2}$$

It can be demonstrated that W_f can be expressed as

$$W_f = ltw_e + \beta l^2 tw_p \tag{3}$$

where w_e is the essential specific work of fracture, w_p is the non-essential specific work of fracture, β is a shape factor of the outer plastic zone, l is the ligament length and t is the thickness of the sample. Dividing W_f by the area of the fracture surface lt, equation (3) gives:

$$w_f = w_e + \beta l w_p \tag{4}$$

In this equation, w_f is the specific total work of fracture, w_e represents the work that is consumed per unit area in the fracture-process zone and represents a material property for a given thickness. The term w_p corresponds to the plastic work dissipated per unit of volume of the material.

Equation (4) shows the linear relationship between the specific total work of fracture w_f and the ligament length. In order to compute the essential specific work of fracture, it is necessary to test a number of samples with different ligament lengths. Then, plotting w_f versus ligament length, w_e can be obtained, by intercepting the straight line with the vertical axis.

EXPERIMENTAL PROCEDURE

The sample used in the experimental procedure can be seen in figure 2. This sample is called DENT, Double Edge-Notched Tension [4].

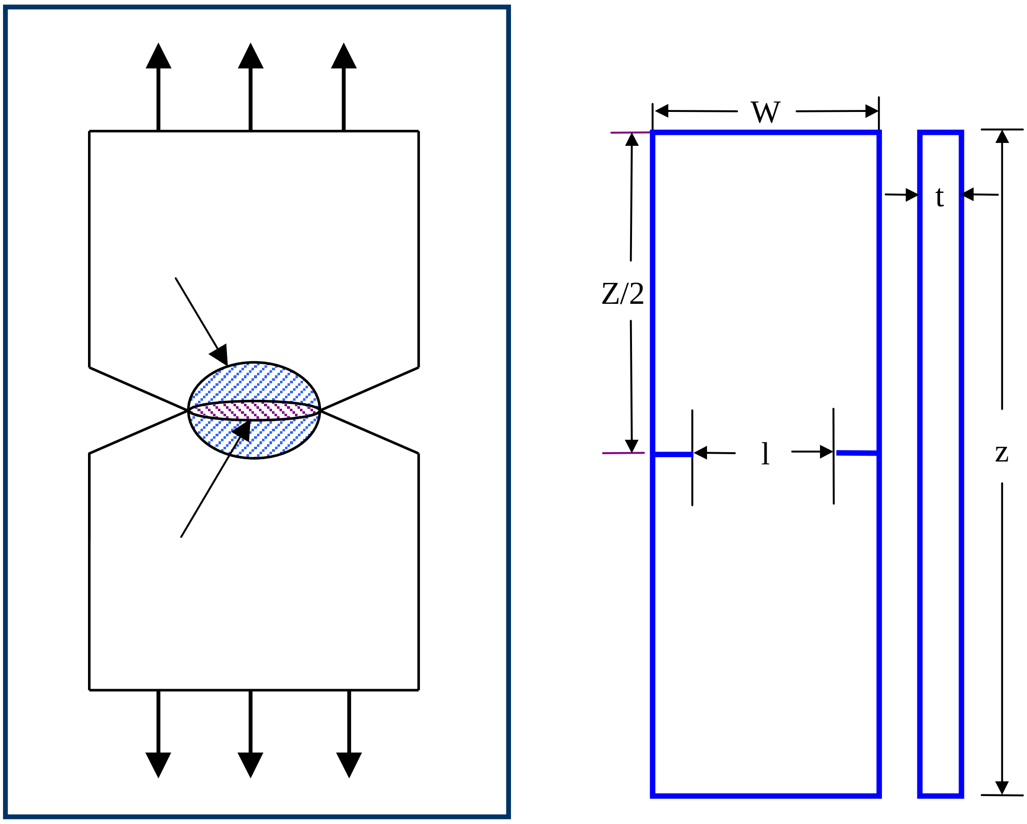

Figure 2.- (a) Schematic representation of the plastic zone in the material; (b) Geometry of the sample.

Some restrictions must be satisfied by these samples. First, the ligament length must be lower than w/3, w being the width of the sample. The objective of this restriction is to avoid the behaviour of the crack be affected by the edge effects. Second, the ligament length must be lower than $2r_p$, where r_p is the radius of the plastic zone which is given by the linear elastic fracture mechanics [5,6] as $\left(\frac{1}{2\pi}\right)\left(\frac{K_C}{\sigma_Y}\right)^2$ for a circular zone. In this manner, the ligament length controls the size of the plastic zone, since the overall length is in plastic deformation when fracture occurs. Finally, in order to induce a plane-stress state, it is necessary that the ligament length be greater than 3 times the thickness [7-10]. These three conditions can be expressed as:

$$3t \le l \le min(w/3, 2r_p) \qquad (5)$$

Two steels were studied in this work, whose composition is showed in Tables 1 and 2.

Table N°1.- Chemical composition of steel 1.

%C	%Mn	%P	N(ppm)	%Al
0.06-0.08	0.4-0.5	0.011	80-100	0.016

Table N°2.- Chemical composition of steel 2.

%C	%Mn	%P	%S	N(ppm)
0.121	0.549	0.0093	0.0104	25-35

The metallographic analysis of both steels, see figure 3, shows a ferritic structure with carbides either inside the grain or in the grain boundaries. For steel 1, the grain size was 2.5 μm and for steel 2, the grain size was in the range 2.8 to 4.1 μm. The difference in grain size are due to the different thicknesses studied in steel 2. The mechanical properties of these steels are showed in Table 3.

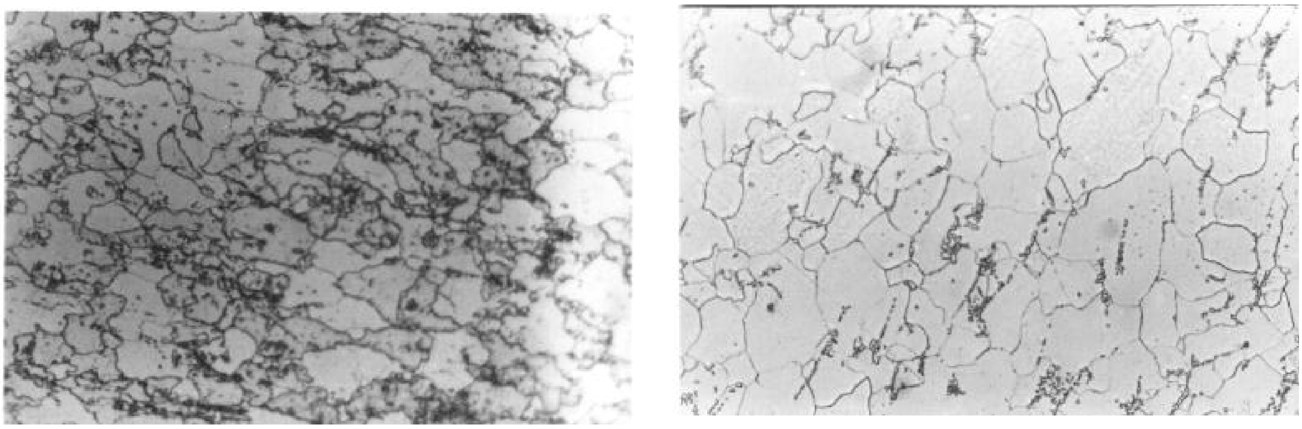

Figure 3.- Microstructure corresponding to (a) Steel 1 and (b) steel 2, as can be seen at 500X in optical microscope. Etched with nital 2 for 20 seconds.

Table 3.- Mechanical and properties of the steel studied.

	E (GPa)	**σ_y (MPa)**	**UTS (MPa)**	**Vickers Hardness (Kg/mm^2)**	**% elongation**	**Thickness (mm)**
Steel 1	173	431	445	116	4.5	0.18-0.3
Steel 2	178	269	386	86	3.4	0.4-1.2

The DENT samples were tensioned in a tensile test machine, plotting the applied load against the displacement. From these data, the curve energy against displacement was constructed. To do this, it was necessary to compute the area under the load –displacement curve. The full area is the total energy for fracture. Then, the total energy for fracture was plotted against the ligament length, obtaining from the intercept to the y-axis, the value of the essential specific work of fracture for each thickness studied. Finally, the essential specific work of fracture was plotted against the thickness of the sample.

RESULTS

Figure 4 shows the load-displacement curves for different ligament lengths. As can be seen in these figures, the load decreases gradually at the final of the test, according to the ductile process of fracture.

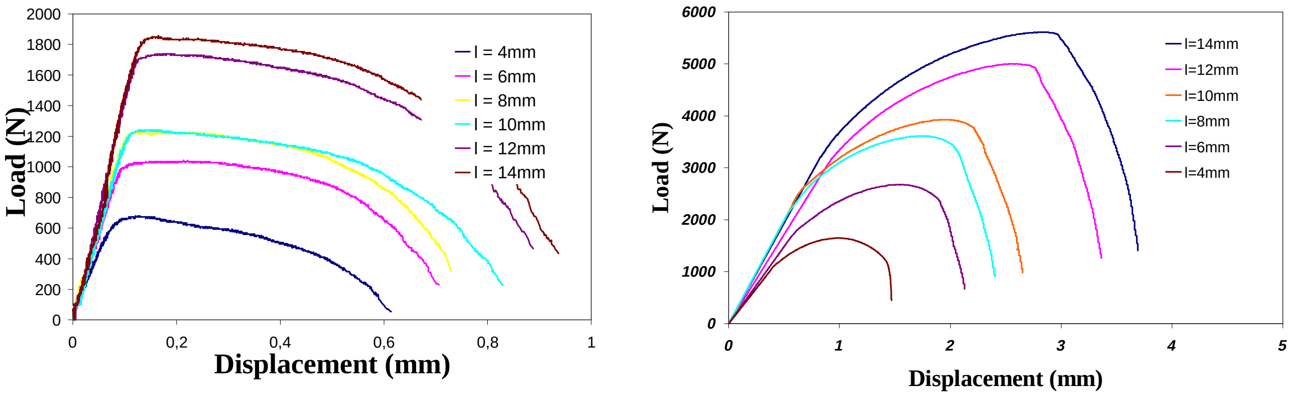

Figure 4.- Load-displacement curve for (a) steel 1; (b) steel 2.

The energy-displacement curves are showed in figure 5. In both cases, the energy increases with displacement.

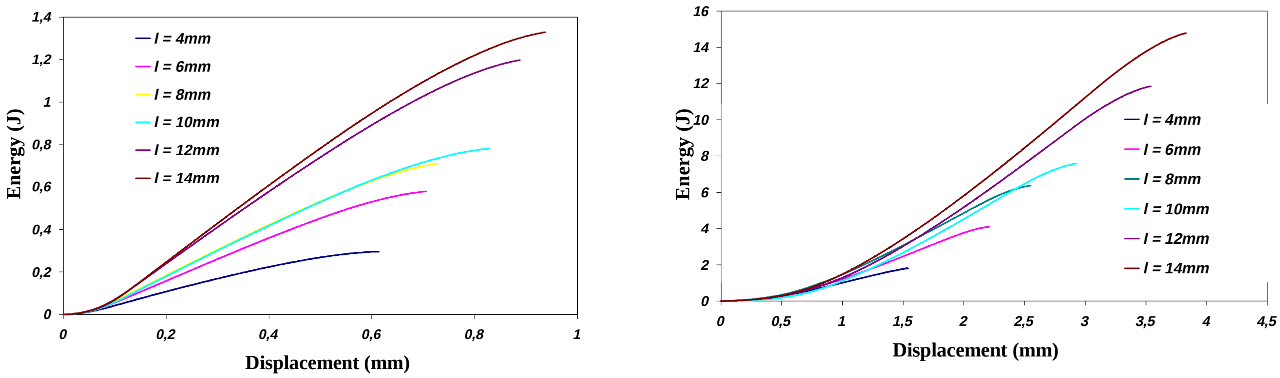

Figure 5. Energy absorbed-displacement curve in fracture for (a)steel 1; (b) steel 2

The energy-ligament length curve for each material shows approximately a linear relationship, as can be deduced from figure 6. In both cases, it was extrapolated the curve for zero ligament length, in order to compute the essential specific work of fracture. This is in accordance with the methodology employed in previous works of the authors [11-15] and in particular with ESIS Protocol [6].

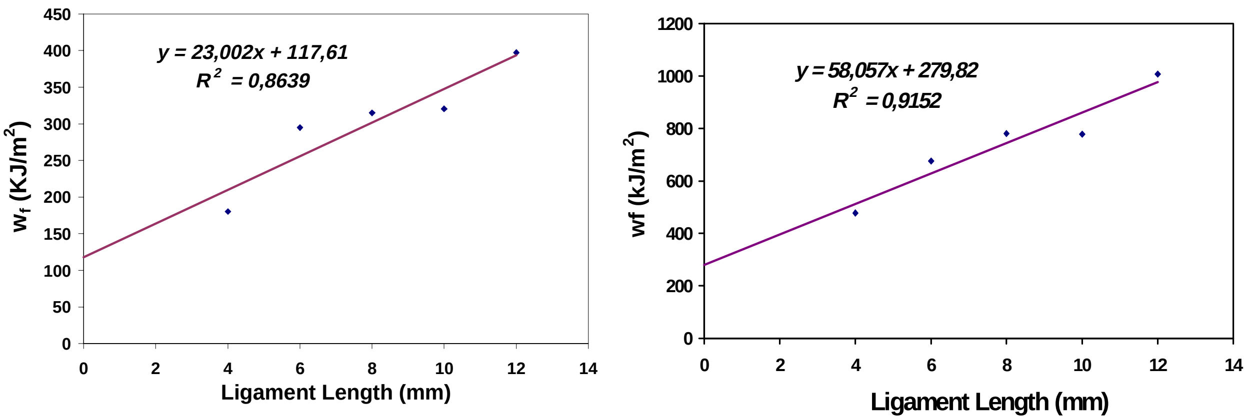

Figure 6. Energy absorbed against ligament length for (a) steel 1; (b) steel 2

The same curves have been obtained for different thicknesses. In figures 7, the values of the essential specific work of fracture against all thicknesses of the material studied are showed. It is possible to conclude that, in the case of steel 1, a linear relationship between essential specific work of fracture and thickness of the material seems to exist. In the case of steel 2, it is possible to conclude the same, although a great dispersion in the experimental data is observed.

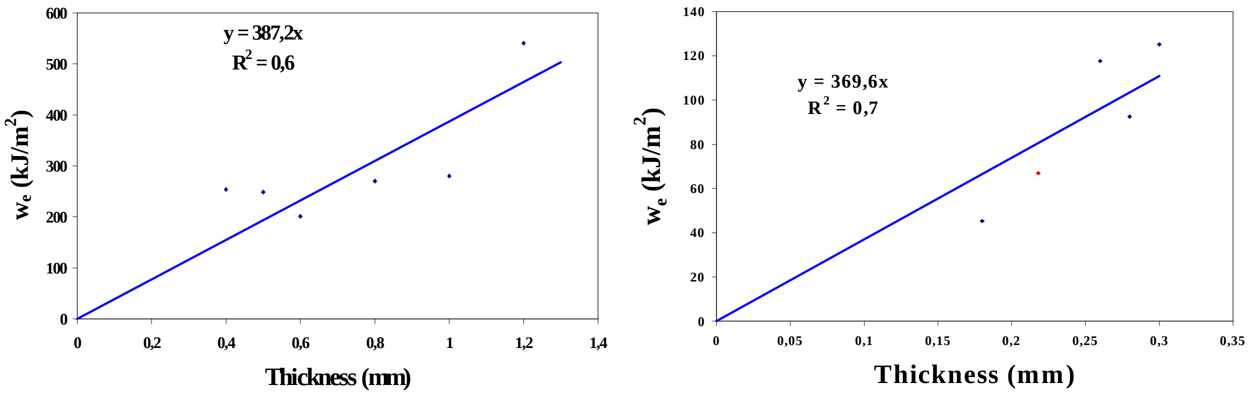

Figure 7.- Essential specific work of fracture against thickness for (a) steel 1; (b) steel 2

FRACTOGRAPHY

As can be seen in figure 8, the appearance of the fracture surface under SEM (Scanning Electron Microscopy) technique, corresponds to a typical ductile fracture. The presence of numerous dimples around voids is appreciated that make evident the ductile fracture process with a great quantity of plastic deformation. According to the fracture theory, these voids are originated by particles of second phase such as inclusions or carbides. In the cavity showed in figure 8, it is possible to observe one of these particles that in this case corresponds to a MnS inclusion, as the EDAX (Energy Dispersive Analysis X-Ray) analysis made to this zone of the sample, shows in figure 9.

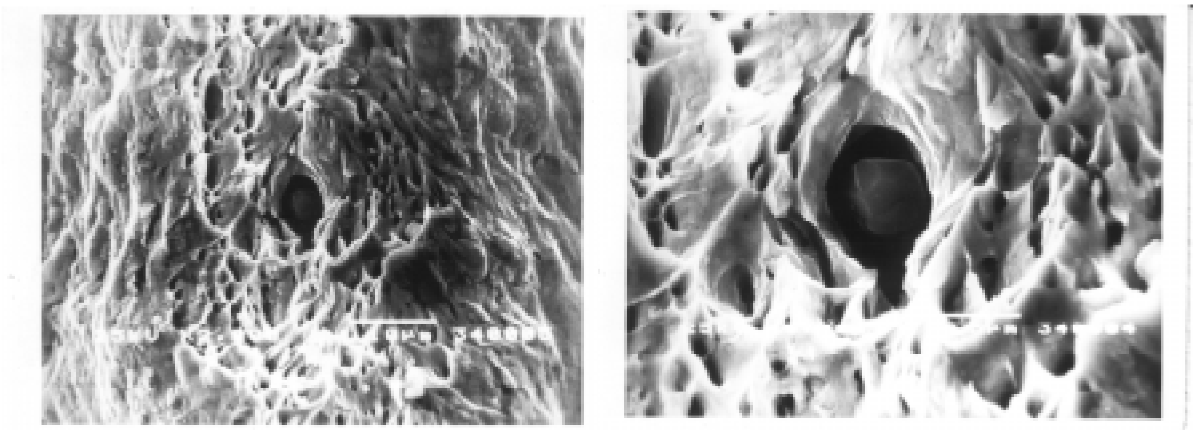

Figure 8. Fractography of DENT sample of steel 1 broken in tension (a) 2000X (b) 3500X.

These observations can be related to the microstructural aspects of both steels, which are showed in figure 3. In both cases, a predominant ferritic structure can be observed, with carbides oriented in the rolling direction. Other particles, such as MnS, were found in the material using SEM and EDAX techniques. This great number of particles, with low cohesion energy with the matrix, breaks the cohesion with the matrix under the application of load. This effect gives origin to a void that concentrates stress, producing therefore, a great quantity of deformation around the void, that accelerates the growing itself, which induces a concentration of stress and so on. Finally, this void that is growing, finds another neighbour void, producing the coalescence of themselves. As can be expected, high deformation energy must be absorbed in this process, giving to the material, a high value of toughness. The evidence of the high plasticity is in accordance with the plane-stress situation, and from the point of view of the microstructure, the presence of numerous dimples around the voids, with high value of plastic deformation can be observed.

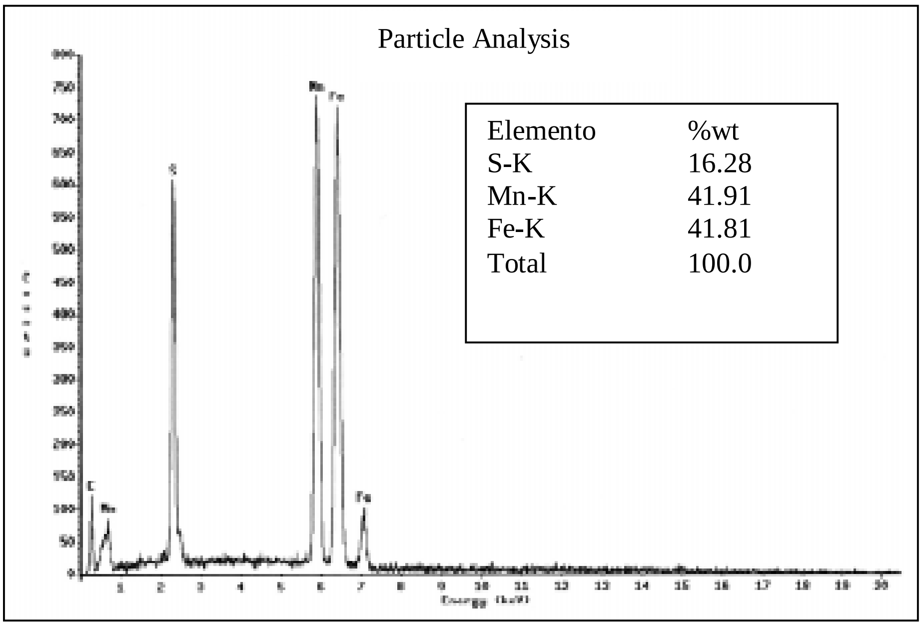

Figure 9.- EDAX analysis over the particle showed ion figure 8.

CONCLUSIONS

The essential specific work of fracture has been measured on two kinds of steels, in accordance to the ESIS 1995 Protocol, in order to characterize the behavior of these materials under the Mode I fracture process.

Different thicknesses of these steels were studied in order to obtain the dependence between essential specific work of fracture and thickness, finding a nearly linear relationship between both variables.

The morphology of fracture corresponds to a typical ductile mechanism that consists of nucleation, growing and voids coalescence, with dimples surrounding the voids.

Numerous particles of, either, Fe_3C or MnS, were observed which can give origin to the voids. These voids, absorb a high quantity of plastic deformation energy, that gives the high toughness value encountered in these materials.

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