Fracture of a 08KP steel in nano-fragmented state

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ABSTRACT

The evaluation of the resistance to the fracture toughness of metals and metal composites that work in the plastic regime requires of the using of highly complex experimental methods and analysis which are not at all standard ones. The increment in the parameters describing the mechanical properties is certainly associated to the origin of internal barriers inside the material which are capable of stopping the free movement of the dislocations and their packing on specific sites of the crystalline structure. The dislocations play an important role on the transmitted energy in the metal during the deformation process. In this work it is analyzed the cryogenic hardness mechanism by deformation, and the features which influence such mechanism. The effectiveness of the hardness treatment of the metal is determined by the two factors: 1) the capacity of the dislocation barrier in order to support the stress between dislocations; 2) the distance between the barriers. In this work, the capacity of the barriers for stopping the dislocations is determined measuring the stress over them.

Keywords: Metals, Metal composites, Mechanical properties, Fracture, Microfragmentation, Nanofragmentation.

1 INTRODUCTION

Now a day, the development of new materials for building is determined not only by the feasibility to use the physical processes for their synthesis, but also in the evaluation of the economical cost for their correct application and rational utility [1]. The use of metals and metal composites beyond of the elastic field requires the understanding of too many basic concepts in order to evaluate the resistance to the fracture of the materials. The existent methods for improving the mechanical properties of the crystalline metals to cause the formation of internal barriers with the capacity of obstruct, in a high manner, the displacements of the dislocations which are an important role on the transmitted energy to the metal during the deformation process at not too much high temperatures [2, 3].

As was mentioned in the abstract, the effectiveness of the hardness treatment of the metal is determined principally by two factors: 1) The capacity of the dislocation barriers for supporting the stress that the dislocations acting over the barriers, 2) the distance between the barriers. While higher the resistance of the obstacles to the free movement of dislocations and the lower the distance between them are, greater the hardener effect is. Actually, the mechanical fracture methods have a dominant position in the description to how evaluate the tendency of the metal resistance to present a fragile fracture. However, the weak point is that, it have been not possible to evaluate in a totally right manner the energy which is required for the origin of a micro-crack; and the principal task resides in to propose a mechanism for understanding its evolution growth to a length in such a way the postulates of the methods of the fracture mechanic are satisfied. Specifically, in the actual step of the development of the mentioned theory, it is proposed only the study of the extreme equilibrium conditions for solids which have macroscopic cracks with a particular geometry and magnitude, and under a specific loading condition. Mechanical parts, with such macroscopic cracks as those which are studied by the methods of the fracture mechanics are, in general, prohibited for their using.

The elapsed time between the start of the crack until this reaches its critical magnitude, how commonly is analyzed by the fracture mechanic, ranges from 60 to 98 percent of the total utile life of the sample. Inside the common concept about of the materials like that is applied in the fracture mechanic theory; it is not possible construct an adequate model about of the origin of a crack, proposed a mechanism which explains its development to get a critical magnitude, and to explain the peculiarities presented in the fractography images of the surface fracture.

It is necessary to recall that, on the development of new metals of high resistance, the use of the experimental methods based on the fracture mechanic generate many problems for the users and researchers.

Many authors treat to interpret the fractographic studies from the fracture mechanic point of view [4], however, there are too many doubts about the interpretation of the results. Considering that the characteristics of the ductility of the fracture are too much important when the capacity of work of a structure is evaluated, emerges the necessity of determine them using samples of small size. Also, the use of small samples methodology is required when new steels of ultra high resistance are formulated, and in the development of new technologies to increase the hardness of the existent steels. In this experimental frame, some results got in 08KP steel samples of low carbon content, are discussed in the present work. Further researching results related with this methodology are also discussed.

2 EXPERIMENTAL

The experiments were carried out using small low carbon content 08KP steel samples. With the aid of a special grips of about 3mm diameter, the cylindrical samples of about 8.5 mm thickness and 1.5 mm diameter dimensions were put on the grips of the test machine. The chemical composition of the steel is shown in table 1. Before the experiments were carried out, some samples were subjected to a normalization treatment, others were subjected to a hardening process which is described in the international patent N°.1786132 [5]. The samples were tested at tension in a servo-hydraulic machine INSTRON 8500 with a deformation velocity about ~$2 \cdot 10^{-3}$ 1/sec, and a temperature of 20°C. In figure 1, it is shown the typical curves of tension for the samples at normalized state, 1 – 1 curve; and at hardening state 1 – 2 curve. From the Figure 1, it can be observed the drastic mechanical behaviour between the hardening and normalized states of the 08KP steel. In the tension curve at hardening state of the sample, is not observed the upper yield strength (yield teeth), also the lower yield strength (yield platform); the yield limit coincides with the rupture limit, the relative elongation decrease in ~ 5 times, when the resistance characteristics increase in 3.5 times.

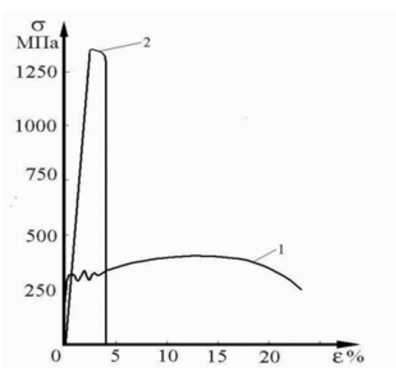

Figure 1: Deformation diagram of the 08KP steel at normalized (1) and hardening (2) states, respectively. $\acute{\varepsilon} = 5\times10^{-3}$ 1/c, T= 20° C.

3 RESULTS

The hardening state of the researched steel was generated by means of the application of a cryogenic mechanic treatment (CMT), which procedure is analyzed in [5], furthermore, for the determination of the optimal parameters of such regime it was used the method detailed in [6]. The explanation to the problem consist in the fact that the plastic deformation of the steel at the hardening state it is localized on the work area where the crack appears, and if the values of the plastic elongation are related, not with the length of the work zone of the sample, but with the length of the zone which experiments the plastic deformation, then the plasticity will be high. The last statement confirms the ductile character of the surface of the sample fracture. The hardening effect during the CMT is achieved as the result of the formation of a great quantity of the internal barriers which blocked the movement of the dislocations. Then, such dislocations are agglomerated at the vicinity of the barriers presenting the capacity of minimized the resulting internal stresses. In Figure 2, it can be observed some aspects about of the character of the microstructure of the hardening state.

Figure 2: Microstructure of the fractures at the normalized state (Top, ×500) and the hardening state (Buttom, ×350)

It can be observed that, as a result of the CMT, the average of the structure acquires a high fragmented character.
The grains which at the beginning were equi-axial should be fragmented causing the formation of small disoriented polygons with a size of the order of 28 to 6 μm. The interior of the polygons is variegated of parallel dark traces. The field of the cells between the edges is divided in fragments of smaller size with magnitudes of the order of 1.8 - 2.6 x 10^{-2} μm (or 18-26 nm).
For the steel at hardness state the shape of its tension curve show a simple scheme of the evolution of the metal fracture. During the loading in the elastic field, it is produced an accumulation of energy inside the volume of the metal in terms of the energies of the elastic fields of the dynamic dislocations, which are inversed related with those dislocations already existent in the metal before the loading application is taken place. The only circumstance that; after the stress achieve their maximum value and the deformation load begins to slowly decrease testify that, the origin of the crack is taking place under a maximum load and its magnitude are lower that the critic, under the which its accelerated growth begins. For this reason, the tension diagram zones between the fracture tensile strength and fracture stress represent stable steps of growth of the crack in order to achieve critical magnitudes, after that, the incontrollable growth begins causing on the specimen the catastrophic fracture. Considering that the origin of the cracks is taking place in a determined critic volume, in which an extreme elastic energy is accumulated for a structural state, and then it is possible to get an equation which permits the evaluation of the surface energy of the generated crack, of which expression is:

$$U \cdot v = 2S \cdot \gamma \qquad (1)$$

where: U- is the specific elastic energy of the volume unity of the metal, v - is the volume where the born of a crack is taking place; γ – is the specific surface energy of the crack; S - is the magnitude of the crack surface.

In the origin of a crack by means of the cracking of the inter-atomic bonds on a surface S, the critic volume for a formation of a crack is equal to S·δ, where, δ – is the aperture of the crack. In order to the formed crack will be stable it is required that δ ≥ 2b. Considering that in the time when the crack is generate $U = \sigma_o^2/2E$, from the equation (1) it should be evaluate the surface energy in the initial time of its appearance as follows:

$$\gamma = \frac{\sigma_o{}^2 \cdot b}{E_r} \qquad (2)$$

Where: b – is the Burgers vector, E_r - is the value of the Young relaxation module.

In accordance with [7], the condition in order to a crack should be developed is the generation of dislocations from its vertex, which starts when the tangential stresses at the front of the crack reach the theoretical value of the resistance. Starting of such assumptions, the equation which permits the magnitude evaluation of the generated crack is proposed as follows:

$$\tau_{th} = \sigma_o \cdot \frac{\sqrt{2}}{2} \cdot \left(l + 2\sqrt{\frac{l}{\rho}} \right) \qquad (3)$$

where: τ_{th} – The theoretical value of the resistance to the displacement, that in accordance with Frenkel [7] $\tau_{th} = G/2\pi$, l - is the length of the generated crack., ρ – is the curvature radio of the crack tip. In order to determine the length of the crack using equation (3), it is considered that ρ ≈ b. The got value of the tensile strength about σ_o=1362 MPa, was obtained considering that, the length of the generated crack was about 102,5 Å.

During the evolution of the generated crack, it is assumed that its rotation ellipsoidal shape is maintained, with the major axe equal to the length of the crack (2l), and the minor axe as its aperture (δ), and then it is possible to get the average length of the crack (l) as function of the applied stresses considering the equation (3). For a crack with this geometry, the curvature radio (ρ) of its tip is equal to:

$$\rho = \frac{l^2}{\delta} \qquad (4)$$

In Figure 3, it is shown the length of the crack as a function of the magnitude of the applied stress at the stable growth step. From the figure it is observed that this part is taking place at two times. At the first step, during 0.075 seconds, the magnitude of the crack is abruptly increased with a velocity of 0.1083 cm/sec. After that, during 10.69 seconds the crack growth with a velocity of about 1.55 10^{-4} cm/sec.

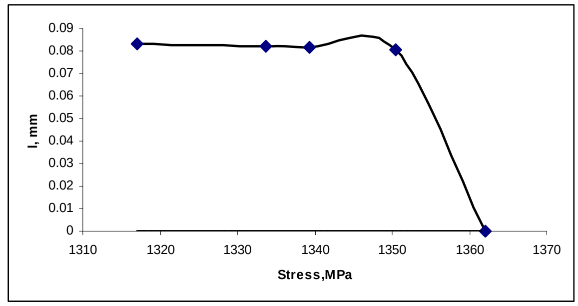

Figure 3: Average length of the crack as a function of the applied stress for the 08KP steel at the hardening state.

Where such average values can be determined using the following equation:

$$\hat{\delta} = \frac{\pi}{2} \cdot \delta, \qquad (5)$$

The corresponding values of the coefficients of the intensity of the stress (K_1) can be got from the know equation of the fracture linear mechanics using a cracking by separation scheme in a plane deformation state and given by:

$$K_1 = \sqrt{\frac{G_1 E}{(1-\nu^2)}} \qquad (6)$$

Where: $G_1 = 2\gamma$, ν – is the Poisson coefficient. The final step of the fracture, corresponding to a catastrophic growth of the crack, can be analyzed in the frame of the linear fracture mechanic [1,8].

Its is well known the tridimensional analytical solution in order to determine the required energy for a crack of disc shape to be opened inside on an asymmetric body and which should be used on cylindrical specimens [7]. This solution was got by means of an integration of a differential equation with the aid of a function of bi-harmonical stresses, for which the Henkel transform with the adequate boundary conditions was used. In order to the boundaries of the crack must be opened in the $u_z(0,0)$ axe, from such solution the following equation is got:

$$u_y(0,0) = \frac{4(1-\nu^2)}{\pi E} \sigma_c l \qquad (7)$$

From the last equation, can be determined the required critic stress σ_c in order to the crack propagation should be taking place. The critic stress σ_c can be substituted in the equation (8) for evaluate the critic coefficient of the intensity of the stress.

$$K_{1c} = \frac{2}{\sqrt{\pi}} \sigma_c \cdot \sqrt{l} \qquad (8)$$

However, the determination of σ_c using the equation (7) for a generated crack of a know length, results higher in comparison with the experimental measurements, such assumption put in dubts its applicability for specimens of small size. For this reason, the coefficient of the intensity of the stresses should be calculated using the following (9) equation:

$$K_1 = \sqrt{\frac{EG}{(1-\nu^2)}} \qquad (9)$$

The last statement has its explanation, - at the front of the tip of the crack huge plastic deformation process are taking place resulting in a substantial increasing of its magnitudes.

4 CONCLUSIONS

The proposed CMT shows its high efficiency on the hardener effect of the low carbon steels. The highly hardening state is reached by the capacity of the CMT for generating a highly fragmented structure of a martensite type during the step of the temple of high velocity. Such fragmented structure can be maintained at ambient temperature as a result of the aging after the realized deformation at low temperature. At the hardening state, the steel showed a fracture of a ductile character besides a significant decreasing of its plastic parameters. Furthermore, the behaviour of the deformation process of the steel at the hardening state is different in comparison to the normalized state. Figure 1 shows clearly such differences. It is well known that, the area below the tension curve should be interpreted like the specific work of the sample fracture. The work of the fracture of the steel at the hardening state is appreciably lower than the normalized state (41,87 MPa and 58,26 MPa, respectively). The comparison of the required energies for a crack is propagated, the energy which is liberated when the samples are broken, shows results which no favours to the normalized state (16,68 MPa for the hardening state and 0,58 MPa for the normalized state). Finally, it is necessary recall that, our investigations were carried out using samples of small size, therefore in the future, it is recommended extrapolate the methodology on samples with size of magnitudes exigent by the fracture mechanic.

Resultados fundamentales sobre el proceso de nanofragmentación de la estructura obtenida por TTC, se reporta en el trabajo sometido a consideración en la Revista NANOTECHNOLOGY.

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