1er. SIMPOSIO TÉCNICO IBEROAMERICANO SOBRE ESTRUCTURAS Y MATERIALES PARA LA CONSTRUCCIÓN

STRESS CORROSION CRACKING AND FRACTURE TOUGHNESS VARIATION OF HIGH STRENGTH STEELS

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ABSTRACT

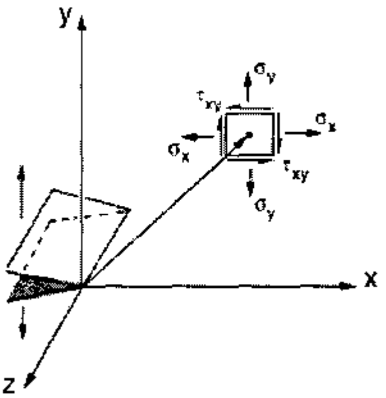
The stress corrosion cracking process is at this moment an unknown mechanism of deterioration. It is a process that implies the joint action of the media, the presence of corrosion or a surface defect and of stress in the metal. Prestressing tendons can suffer SCC jointly with hydrogen embrittlement which dramatically changes not only the type of fracture (from ductile to brittle) but also the kinetics of the process leading to unexpected collapses. The metal should be resistant to this type of process which can be characterized by its toughness and therefore by its damage tolerance.
This research shows that the Fracture Toughness change when the steel corrodes, questioning the idea that is an intrinsic characteristic of the material. The reduction in the fracture toughness of steel wires when they are in contact to aggressive media involve that the material fractures with a lower crack depth for the same stress level. That means that the material becomes less damage tolerant, which implies that it is necessary to detect defects of smaller size, as for example, small notch, pits or superficial cracks. In the paper some results of the percentage of decrease of the toughness of prestressing wires suffering corrosion are presented.

1. INTRODUCTION

Concrete has an alkaline pore solution (pH > 12.6) that guarantees the passivation of steel reinforcement in addition to be a physical barrier against the penetration of environmental aggressive [1-7]. This protection can be maintained indefinitely until an aggressive element in enough concentration reaches the bar. The most common causes of corrosion are the carbonatation of the concrete cover, which produces a reduction of the pH of pore solution, and the penetration of chlorides, which induces pitting corrosion.

A particular case of corrosion of the steel embedded in concrete is the Stress Corrosion Cracking (SCC), which can appear in prestressed structures. The SCC is produced by the simultaneous action and synergy of a mechanical tension and a corrosive media. Nucleated at the steel surface, the result is the appearance of microscopic cracks that are penetrating and inducing the brittle failure of the wire, due to a triaxial stress condition.

The Fracture Toughness (K_{IC}) is one of the most important parameters in (23) Fracture Mechanics. Prestressed wires present high fracture toughness and, until now, this parameter has been considered as a characteristic of the materials. The fracture toughness is one of the fracture criteria. This parameter is based on the knowledge of the stress ranges and displacement in the surroundings of the crack, that is to say, is based on the Stress Intensity Factor (K_I) (figure 1). Therefore, the fracture takes place when the stress intensity factor reaches the condition: $K_I=K_{IC}$.



$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)$$

Figure 1. Stress intensity factor.

There are a standard to measure the fracture toughness: ASTM E 399-90 (1997): "Standard Test for Method Plane-Strain Fracture Toughness of Metallic Materials". This standard provides details on the geometry of the specimens (Single Edge, Compact, Arc, etc.) and the minimum thickness based on the fracture toughness of the material and its elastic limit. This indicates that the fracture toughness varies with the thickness, decreases as increases the thickness until reaching a constant value from a big thickness [8]. In addition, the fracture toughness depends on the rate of the test and the temperature. Some authors [9-11] have shown the effect of the fatigue in the top of the crack. The cycles of load can produce the plasticity of the crack, which influences as well in the behaviour of the material.

However, it has not been reported the change of the fracture toughness due to the action of the media. Providing a certain material, it is assumed that the fracture toughness remains constant as a material characteristic [8]. Present work will study this aspect. The reduction of the fracture toughness implies that the material, for a same tensional level, fractures with a defect much smaller. That is to say, the material becomes less tolerant to the damage, which implies that it is necessary to detect defects, like for example, small notches, superficial pits or cracks.

In order to support this statement tests of high strength steel in carbonated solutions are performed [12-18]. In these tests, instead of generating the crack by fatigue, it is generated by means of controlled electrochemical and mechanical conditions. After that, it is possible to estimate the fracture toughness in a simple test. The obtained results show decreases around 30-40% of the fracture toughness with respect to the fatigue method value.

2. MATERIAL

A steel of eutectic composition have been tested in two conditions: **cold drawn steel** (1510 MPa Yield Strength) and the **modified parent pearlitic steel** (1300 MPa Yield Strength). The chemical composition of both is therefore the same and it is shown in table 1.

Table 1. Chemical composition of pearlitic high strength steel ($\%_w$).

C	Si	Mn	P	Cr	Ni	S
0.8	0.2	0.7	≤0.02	0.20	0.074	≤0.03

Parent pearlitic steel has treated thermally to a temperature about 250 °C during 15 minutes [19]. The purpose of this treatment is to increase the yield strength from 950 MPa of the raw material to 1273 MPa. The value of the fracture toughness for this material is $\mathbf{K_{IC} = 58\ MPa\ m^{0.5}}$ [6]. And, the fracture toughness value for cold drawn steel is 107.9 MPa $m^{1/2}$ [20].

The samples were mechanized to a diameter of 2.5 mm and a length of 13.2 mm. In this case it is not possible to obtain standardized geometries, and then it is necessary to test cylindrical samples. They have been prepared as shown in figure 2.

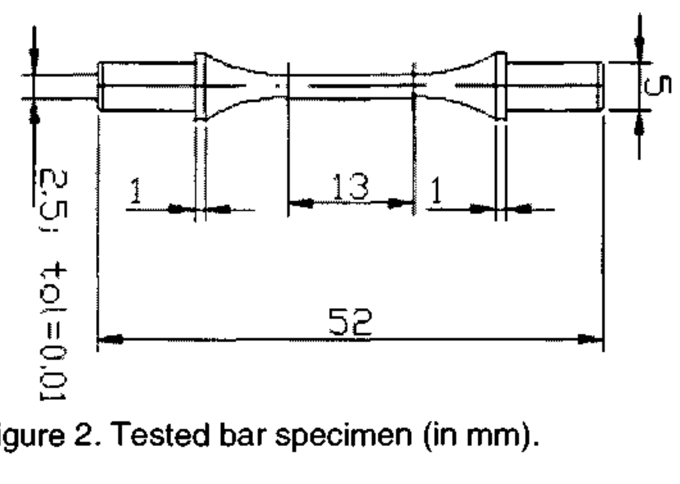


Figure 2. Tested bar specimen (in mm).

The mechanical properties of steel are given in Table 1 according to the number of sinking passages, from departure parent steel to the commercial cold drawn steel [20]. The parent steel used in the tests is the corresponding to a single sinking passage and treated thermally to 250 °C during 15 minutes, whereas the cold drawn steel is the commercial one of 6 passages of sinking. As additional information it has to be said that, the behaviour of cold drawn steel and parent steel are not elastic linear, but elastic-plastic.

Table 2 shows as well, for each passage of sinking, the elastic module (E), the elastic limit (σ_{02}), the fully factored load (UTS) and the parameters corresponding to the equation of Ramberg-Osgood (P, n):

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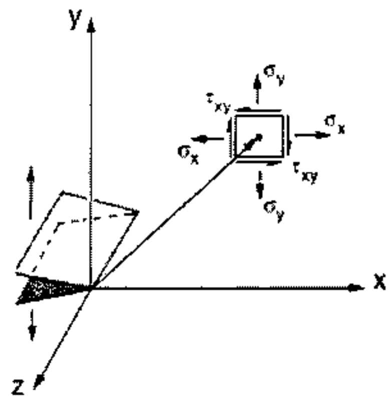

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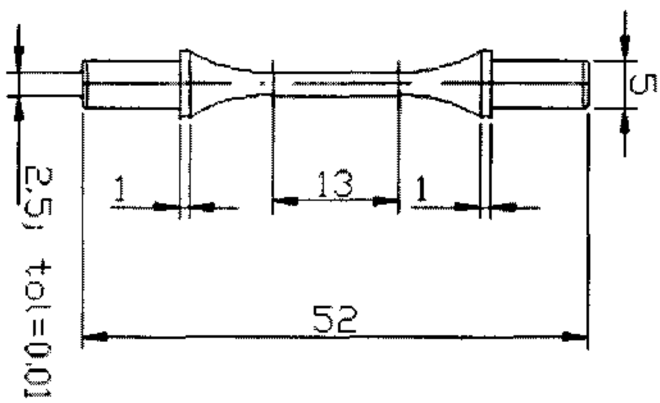

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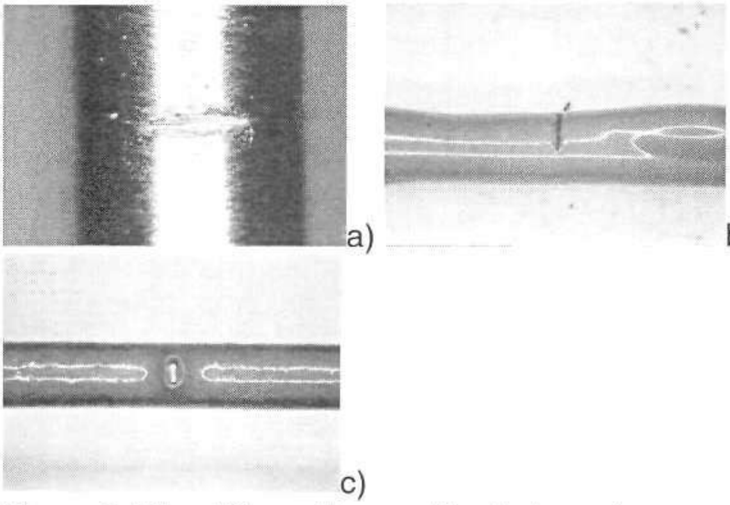
$$\varepsilon = \sigma/E + (\sigma/P)^n \quad \text{Equation 1}$$

Table 2. Mechanical properties of cold drawn steel in function of 6 cold drawn sinking passages. The parent steel used in the paper is that of 1 sinking passage and after thermally treated at 250 °C.

Steel (Sinking passages)	0	1	2	3	4	5	6
E (GPa)	197.4	201.4	203.5	197.3	196.7	202.4	198.8
σ_{02} (GPa)	0.686	1.1	1.157	1.212	1.239	1.271	1.506
UTS (GPa)	1.175	1.294	1.347	1.509	1.521	1.526	1.762
P (GPa)	1.98	2.26	2.33	2.49	2.5	2.74	2.34
n	5.89	8.61	8.7	8.45	8.69	7.98	11.49

3. METHODOLOGY

A set of tests were carried out to localize the generation of single pit and avoid depassivation in the rest of the surface. The more realistic conditions are based in the generation of a crack by electrochemical dissolution from a pit [13, 17], which may represent better the reality than to generate the crack by fatigue. After several trials, epoxi coating was used in order to avoid depassivation by generation of various pits (figure 3). A notch artificially made to leave the steel surface in contact with the solution was used to reproduce a single pit. The best solution is thar shown in figure 3b.



a) b) c)

Figure 3. The different types of tested specimens: a, b, c and d according to the text.

In the test method the mechanical and electrochemical parameters are combined and it is made up of the following stages:

1. ***Fixed potential test in the media:*** The specimen is immersed in a solution of sodium bicarbonate at constant temperature. A fixed potential is applied, during around 100 hours, simultaneously a data logger registers the current. The specimen is strained to 80% of its yield strength. The objective of this stage is to generate an anodic zone and control the crack growth. After this stage, the specimens are removed from the solution and dried.

2. ***Slow strain rate test in air:*** SSRT is performed in air at a rate of $3*10^{-7}$ s^{-1} in order to determine the fracture toughness. It is possible to obtain the fracture toughness using the fracture mechanics calculations from the stress and crack size data.

3. ***Scanning Electron Microscope analysis (SEM):*** In order to examine the fracture surface is used a scanning electron microscope. From this fractographic analysis is possible to evaluate the size of the crack in the fracture surface and the existence or not of brittle zones. In addition it is possible to determine the reduction of area, the different zones of surface of fracture and formed oxides.

4. RESULTS

Once selected the right method of concentration of the damage, some tests were carried out in order to know the influence of the applied potential on the crack propagation at constant load. The potential resulting more sensitive to induce SCC is -275 mVAg/AgCl in the used bicarbonate solution.

Figure 4 shows two different behaviours. It is possible to see an example of a test for a material without defects. In the right part it is shown the curve corresponding to a material that has a crack generated in bicarbonate solution. The fracture for first is completely ductile (figure 5) with the formation of micro-voids, whereas for the second case is completely brittle (figure 6).

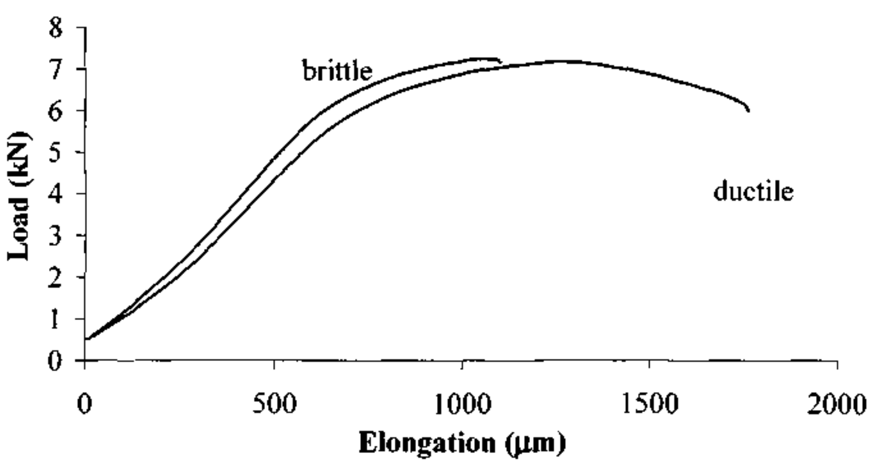


Figure 4. Ductile behaviour versus brittle behaviour.

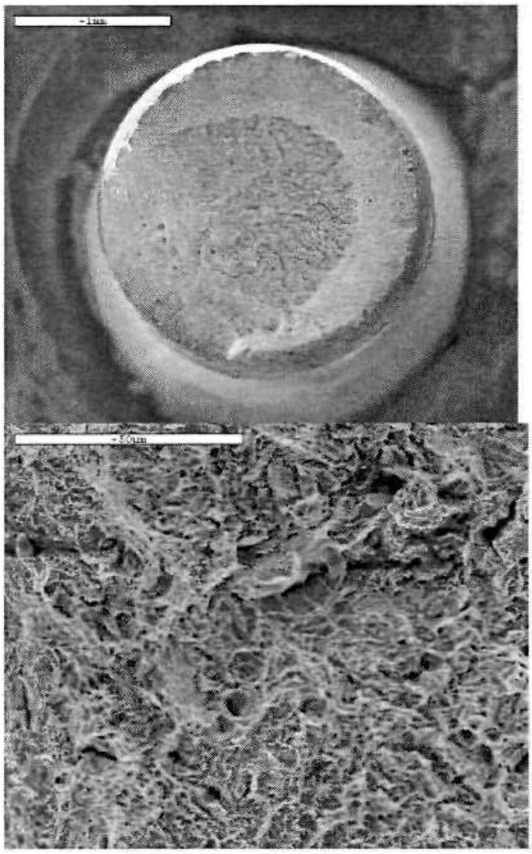


Figure 5. Ductile surface of fracture.

The surface of fracture of one of the wires is shown in figure 6. This type of fracture is characterized by a small area reduction and the fracture takes place in the same plane of the crack. In the image on the right, it can be observed the top of the crack and the mechanical fracture. This mechanical fracture is characterized by the appearance of brittle zones called cleavage.

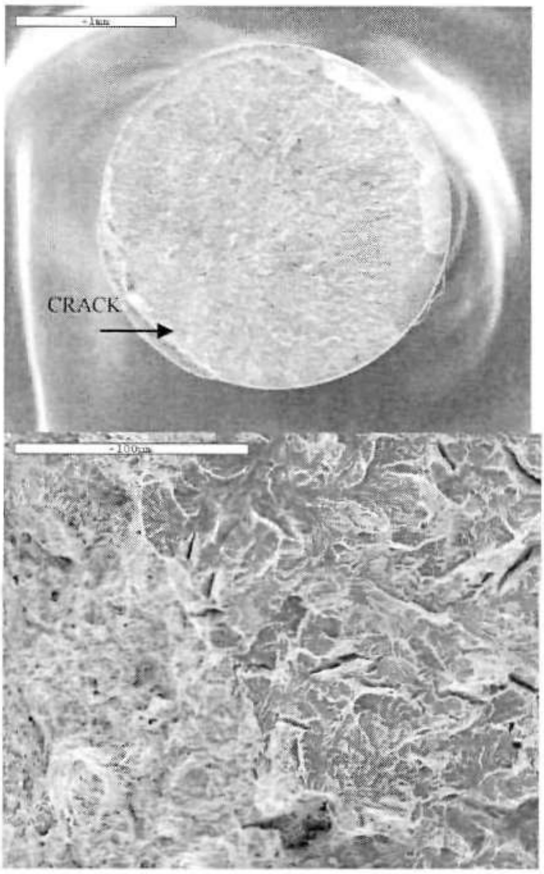


Figure 6. Surface of brittle fracture.

5. DISCUSSION

Due to limited size of the samples, prestressed steels cannot be prepared to obtain standardized specimens for testing fracture toughness of the material (ASTM E399-78) and therefore other approaches are necessary. For the case of a cylindrical geometry of the material, the calculation of the stress intensity factor and the criterion of fracture can be calculated through Valiente and Elices's equation [8] or through Levan and Royer's equation [21]. The above mentioned authors have assumed that cracks along the whole perimeter of the specimen are formed and the superficial cracks have semi-ellipse shape (figure 7). Equation 2 and 3 give the expression corresponding to the stress intensity factor for a superficial crack with semi-elliptical form according Valiente and Levan's work.

$$\frac{K_I}{\sigma\sqrt{\pi a}} = \sum_{i=0\, i\neq 1}^{4} \sum_{j=0}^{3} C_{ij} \left(\frac{a}{2R}\right)^{i} \left(\frac{a}{b}\right)^{j}$$

Equation 2

$$\frac{K_I}{\sigma\sqrt{\pi a}} = \sum_{i=0}^{3} \sum_{j=0}^{3} \sum_{k=0,2,4,6} C_{ijk} \left(\frac{a}{R}\right)^{i} \alpha^{j} \left(\frac{s}{s_m}\right)^{k}$$

Equation 3

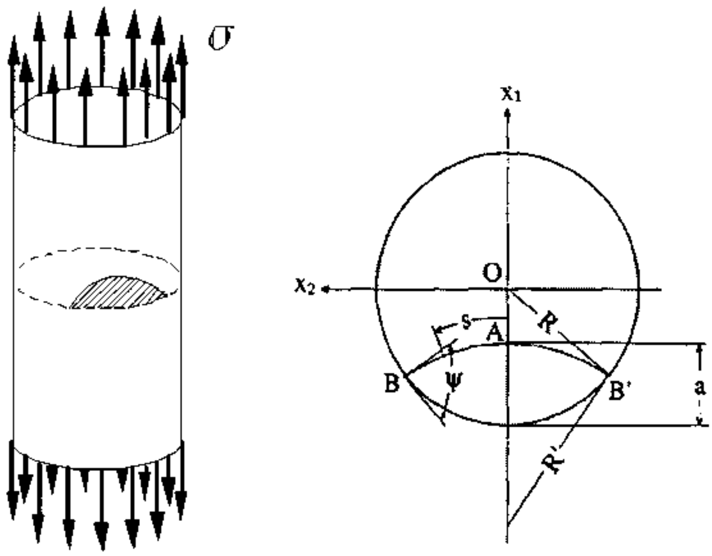


Figure 7. Superficial crack in a wire.

However, the two previous equations have two main limitations to be applied in this study. Firstly, both are only applicable to linear elastic materials. And secondly, the geometry of the crack obtained by stress corrosion cracking must be for form factors = a/R ratios smaller than about 0.5 which is smaller than those observed in our experimentation [13, 17].

Both equations are represented in figure 8. Until a depth of cracks an around 0.5 times the radius R, it is observed quite good accordance between the predictions of both equations. It is worth noting that, for greater depths of crack, as it is the case of those observed by us in prestressing wires, the value of stress intensity factor calculated from the equation of Levan is much higher than that one calculated by the equation of Valiente.

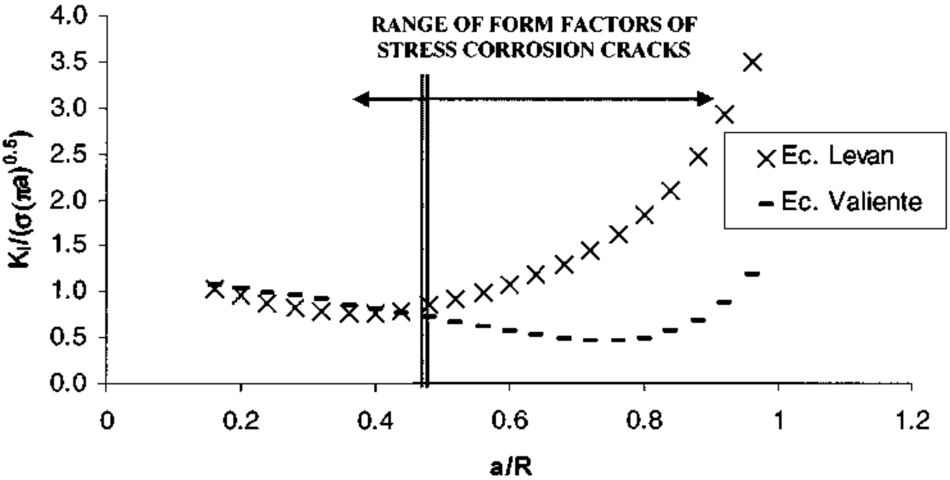


Figure 8. Comparison of notch form factors calculated by means of Valiente et al. and Levan et al. equations for specimens of cylindrical shape.

For so acute cracks in cylindrical specimens it has not been found a rupture criterion that allows considering in a simple manner. Then, present paper shows previous calculations about stress intensity factor for a bar with a crack geometry similar to that generated by stress corrosion, from solving the Integral J obtained by simulation with the ABAQUS Program [22]. Figures 9 and 10 depict the values of K_I so calculated, for the Cold drawn and Parent steels of 2.5mm diameter wire.

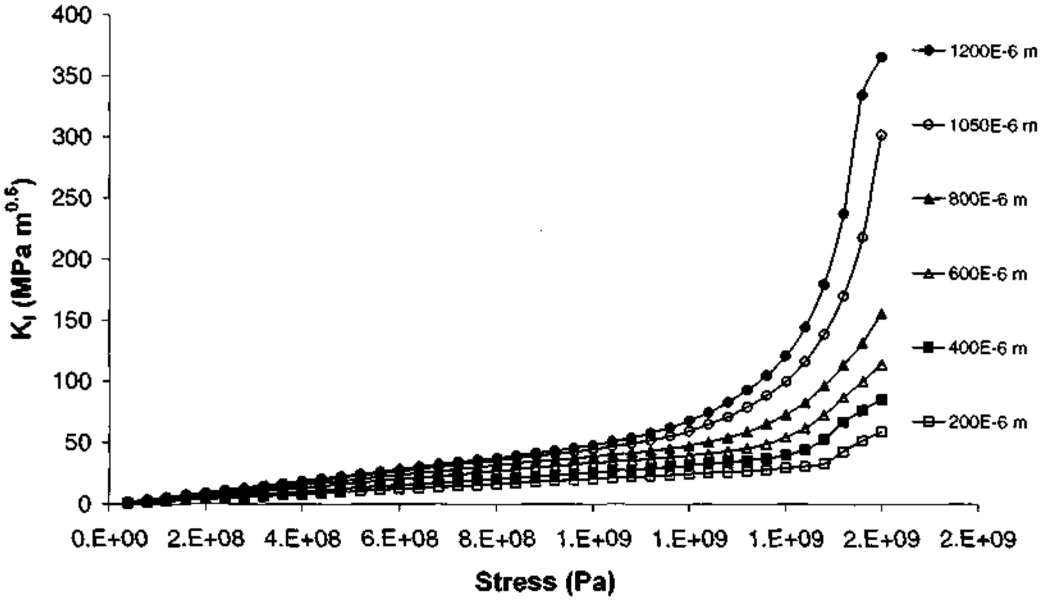


Figure 9. Values of K_I for the Cold drawn steel calculated from the Integral J.

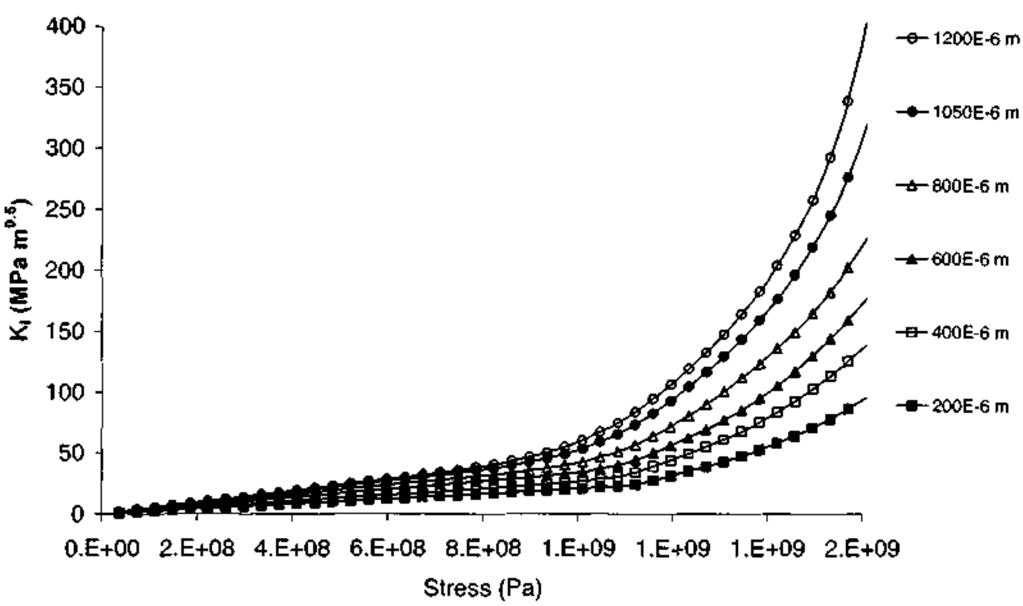


Figure 10. Values of K_I for the Parent steel calculated from the Integral J.

Figure 11 and 12 show the values of the fracture toughness for cold drawn and parent steel. The fracture toughness of the cold drawn steel is higher than parent steel one, although it can be distinguished a large variation of the fracture toughness in both materials. In all cases it is achieved very smaller values, around 50 MPam$^{0.5}$ or less than the nominal ones. This means that the damage tolerance is reduced dramatically by the media, because when the crack grows up by stress corrosion cracking, the fracture toughness can be reduced around 40%.

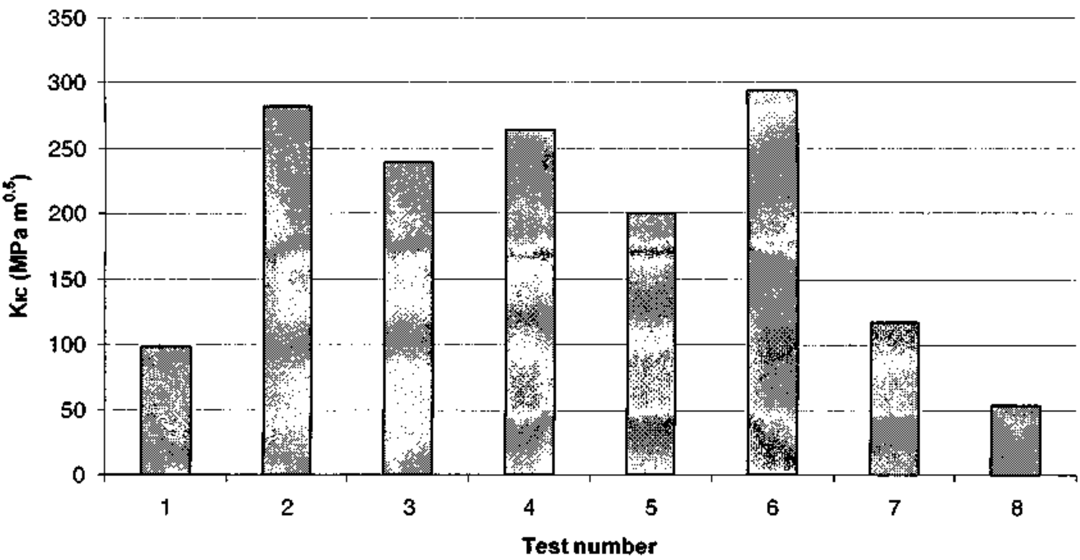


Figure 11. Fracture toughness of cold drawn steel before stress corrosion cracking test.

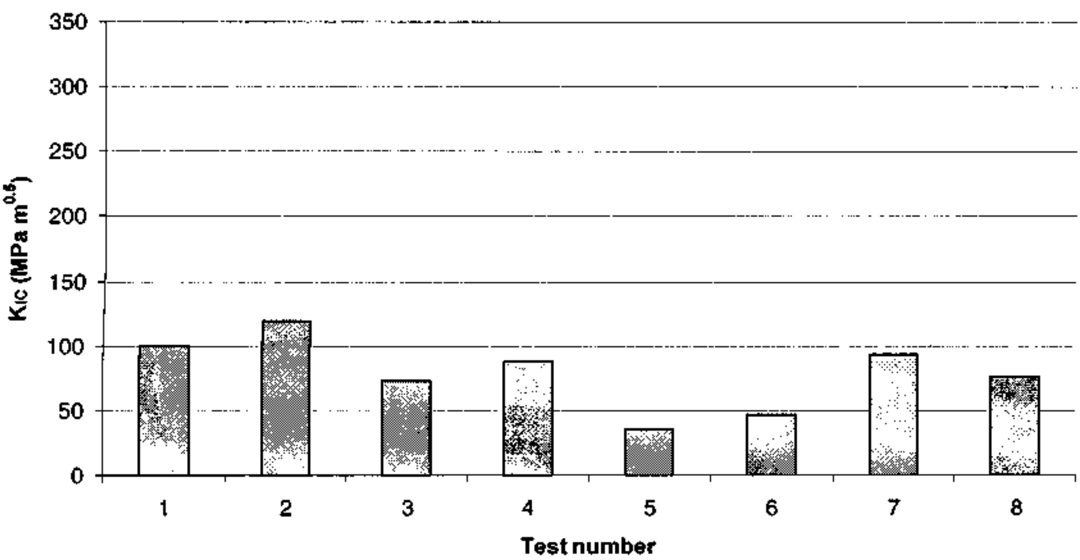


Figure 12. Fracture toughness of parent steel before stress corrosion cracking test.

This reduction indicates the need to reconsider the crack depth needed to develop a brittle failure in the case of corroding high strength steels and therefore, to reduce the expected damage tolerance of these steels when they develop cracks by stress corrosion.

6. CONCLUSIONS

The fracture toughness of metals has been considered a material characteristic with fixed values that are normally determined by means of fatigue tests. Present results obtained from steels specimens coated with epoxi resin, were the crack is induced by corrosion on a notch made in the coating, have indicated that the toughness is significantly reduced when the material is immersed in media inducing stress corrosion cracking processes. Although these tests should be extended to other media in order to know how much this conclusion regarding prestressing steels, it is an indication of a need to review the damage tolerance of prestressed structures in some contaminated atmospheres.

7. ACKNOWLEDGMENTS

The authors wish to thank Ministerio de Fomento of Spain for the funding the accomplishment of the project "Not destructive methods and strategies for the control of the corrosion in pretested steels", the INGENIO 2010-CONSOLIDER Project on "Safety and Durability of Structures: SEDUREC" and, specially, to Prof. Gustavo Guinea (UPM).

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