EVOLUTION OF J_R-T_R CURVES WITH LOW TEMPERATURE AGING OF DUPLEX STAINLESS STEELS

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This work describes a study performed on the evolution of J_R-T_R curves with low temperature (280-400°C) aging for three different duplex stainless steels. The application of a phenomenological model relates the fracture initiation parameter J and the tearing modulus with the percentage of ferrite in the fracture path. With this it is possible to determine the J_R fracture resistance curves and the corresponding J_R-T_R curves.

INTRODUCTION

Cast stainless steels have been widely used for many years in the chemical, oil and power generation industries. These steels usually have a duplex microstructure of ferrite distributed in islands throughout the austenite matrix. Ferrite presence in the duplex structure principally increases the resistance to hot cracking and additionally improves the strength, stress corrosion cracking resistance and weldability.

However, several studies [1-3] have highlighted that these steels are susceptible to aging embrittlement processes with low temperature aging (280-400°C), because of microstructure transformation mechanisms like spinodal decomposition of ferrite and G phase precipitation in ferrite. It has been shown that aging processes embrittle the material, increasing the ferrite hardness and decreasing the impact toughness of these materials. Embrittlement has principally been observed from the evolution of the impact resistance-temperature curves, C_v-T. As these curves are not valid for design purposes other material parameters should be found for components design. One example of such is the J_R curve from which it is possible to determine the initiation J, and the tearing modulus, T_R, associated with crack propagation. Once this information is known, the J_R-T_R can immediately be obtained. Obtaining these design parameters is the main objective of this work.

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MATERIAL

Table 1 shows the chemical composition and ferrite content of the three steels analysed, named 12F, 18F and 22F after their ferrite content. 12F is a commercial CF8M duplex stainless steel taken from a valve aged in service for 10 years at ~280°C. 18F and 22F are similar duplex steels obtained from experimental casts.

TABLE 1- Chemical composition and ferrite content of the studied CF8M steels.

STEEL	C	Mn	Si	Cr	Ni	Mo	%Ferrite
12F	0.035	0.70	1.10	18.6	10.4	2.00	12.2
18F	0.076	0.83	1.25	19.4	9.6	2.29	17.8
22F	0.045	0.82	1.23	18.4	8.9	2.36	21.6

The overaging treatments performed on the 12F steel at 280, 350 and 400°C, reached up to 18000, 14000 and 14800 hours, respectively. For the 18F steel and 22F different aging treatments at the three temperatures have also been performed, up to a maximum value around 10000 hours.

EXPERIMENTAL

Fracture toughness evolution

Fracture toughness at room temperature was determined by J-integral R-curve, following European Recommendations ESIS P1-92 [4], and the unloading compliance single specimen method. CT specimens, 20 mm wide, were used, with 2 mm deep sidegrooves machined after fatigue precracking. Figures 1a and 1b show the J_R curves for the 12F steel aged at 280 and 400°C respectively. Figure 1c shows the same for the 22F steel at different temperatures. These figures demonstrate the important influence of aging on toughness such that fracture toughness clearly decreases with longer aging times at any temperature between 280 and 400°C.

From de J_R curves fitted by means of the power function

$$J_R = A \cdot \Delta a^D \tag{1}$$

the non dimensional tearing modulus was determined [5]

$$T_R = \frac{E}{\sigma_0^2} \cdot \frac{dJ_R}{d\Delta a} \tag{2}$$

where E is the Young modulus and σ_0 is the yield strength. The J_R-T_R curves are calculated from equations (1) and (2). Figure 2 shows the evolution of the J_R-T_R curves obtained from the curves of Figure 1. It can be clearly seen how the stable zone reduces with greater aging and embrittlement.

Fractographic analysis

A fractographic study was made using scanning electron microscopy (SEM) to quantify ferrite presence on the fracture surface. Figure 3a shows a fractography of the unaged 12F steel. The fracture type was very ductile caused by microvoids coalescence in austenite and no presence of ferrite was found. Generally, the percentage of ferrite in the fracture path increases with aging. Figure 3b shows an example of this. Table 2 shows the maximum values of the ferritic fraction present on the fracture surface for each steel. The aging time in hours at 400°C has been added after each X_α value.

TABLE 2- Maximum fraction of ferrite on the fracture surface of J test.

STEEL	12F	18F	22F
X_α	0.13 (14800 h)	0.23 (10000 h)	0.27 (9650 h)

PHENOMENOLOGICAL MODEL

Using the exhaustive fractographic study a phenomenological fracture model was developed [6]. The crack initiation parameter $J_{0.2/BL}$ and the dimensional tearing modulus for a crack length value of Δa = 1 mm, $T_R^* = A \cdot D$, were related to the percentage of broken ferrite on the crack surface by using the following equations

$$J_{0.2/BL} = J_{0.2/BL}^{\gamma} \cdot X_\gamma \left(1 - \mu_J \cdot X_\alpha\right) \quad (3)$$

$$T_R^* = T_R^{\gamma} \cdot X_\gamma \left(1 - \mu_T \cdot X_\alpha\right) \quad (4)$$

where X_γ and X_α were, respectively, the unitary fractions of austenite and ferrite on the crack surface and $J_{0.2/BL}^{\gamma}$ and T_R^{γ} are values associated with austenite which coincide with the as-received values of each steel because all fracture occurs through austenite in the unaged materials. The parameters μ_J and μ_T are related to the effect of the broken ferrite surface on the $J_{0.2/BL}$ and T_R^*, respectively. These parameters come from the following experimentally obtained equations

$$\mu_J = 2.1 + 9.5 \cdot exp\left(-9.9 \cdot X_\alpha\right) \quad (5)$$

$$\mu_T = 2.1 + 5.2 \cdot exp\left(-9.3 \cdot X_\alpha\right) \quad (6)$$

APPLICATIONS

Figures 4a and 4b show the $J_{0.2/BL}$ and T_R^* predictions for the three steels using equations (3) and (4) against the experimental values. These predictions have a correlation coefficient over 0.94 in both cases. Generally, the resulting predictions give an error of less than 20%, and those over 20%, are always on the safe side.

Using equations (3) and (4) along with (5) and (6) it is possible to obtain the J_R curve for a given aging condition, knowing the fraction of broken ferrite on the fracture surface, and the $J_{0.2/BL}$ and T_R^* values obtained from the initial J_R curve for a given steel. Figure 5 shows how a fracture resistance curve can be adjusted from the initiation J value and the tearing modulus for $\Delta a = 1$ mm. Once the J_R curve is predicted, the J_R-T_R curves can immediately be deduced. Figure 6 shows the excellent fit obtained between the J_R curve predicted by the model and the experimental curve for the 22F steel aged for 3300 hours at 400°C.

CONCLUSIONS

The results obtained clearly demonstrate the important loss in toughness suffered by duplex steels when they are aged at temperatures in the 280-400°C range. This can be seen in the evolution of both the J_R and the J_R-T_R curves.

The toughness of aged duplex steels is directly determined as a function of ferrite presence in the fracture path (X_α). Based on this parameter along with the unaged toughness, a phenomenological model has been applied which predicts, independently of material and with margins of error below 20%, the experimental behaviour observed.

The model is supported by the connection established between aging and embrittlement through the local presence of ferrite in the fracture path, i.e. through its participation in local fracture mechanisms. Ferrite presence in the fracture path increases with aging. The aging of these steels establishes local ferrite embrittlement reducing its fracture energy and therefore producing local conditions around a defect or crack which are favourable for provoking a greater number of ferrite islands broken by cleavage. When these broken ferrite islands are reached, the material's overall fracture energy reduces proportionally with the number of said islands.

ACKNOWLEDGEMENTS

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REFERENCES

[1] A. Trautwein & W. Gysel: *Stainless Steel Casting*, ASTM STP 756, 165-189 (1982).

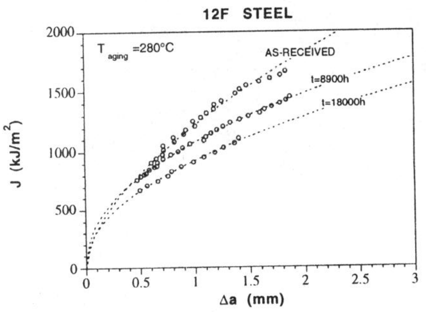
[2] J.P. Massoud, M. Bethmont, & J. Champredonde: in Proc. of Duplex Stainless Steels'91, Beaune, Oct. 28-30, 1991, p. 93.

[3] H.M. Chung: Int. J. Pres. Ves. & Piping, 1992, vol. 50, p. 179.

[4] ESIS P1-92, "ESIS Recommendations for Determining the Fracture Resistance of Ductile Materials", European Structural Integrity Society, January 1992.

[5] M.F. Kanninen & C.H. Popelar: *Advanced Fracture Mechanics*, Oxford University Press, New York, NY, 1985.

[6] L. Sánchez: Doctoral Thesis, Mar. 1996, University of Cantabria, Spain.



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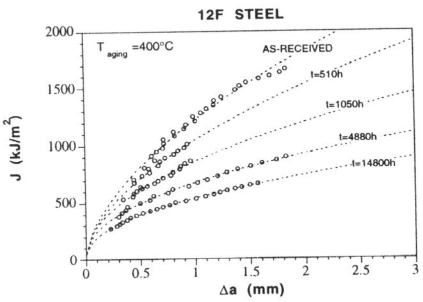

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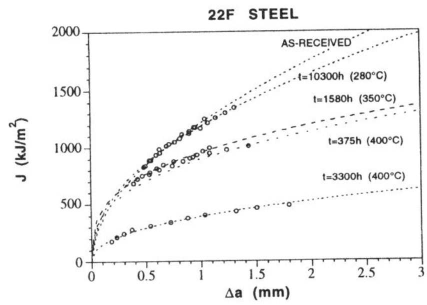
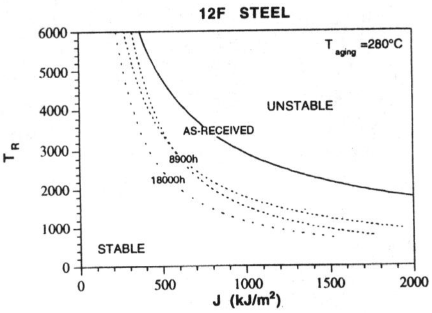


(c)

Figure 1. Evolution of J_R curves.



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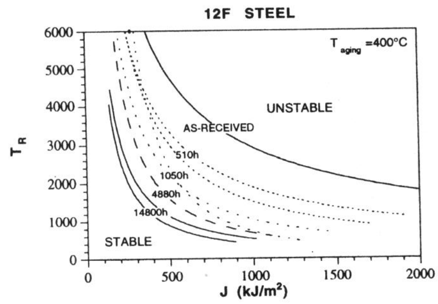

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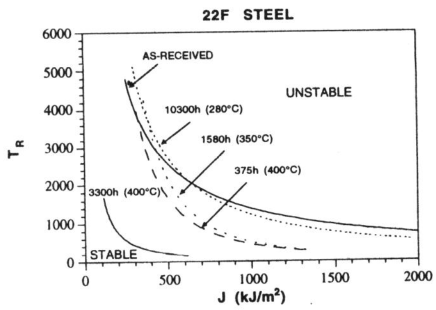

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Figure 2. Evolution of J_R-T_R curves.

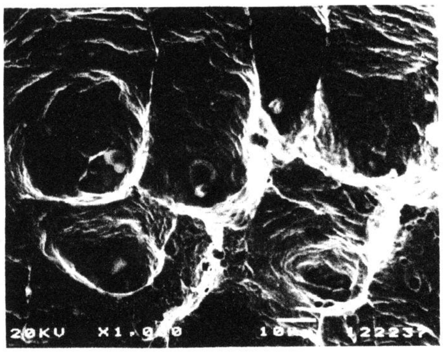

Figure 3a. Fractography of 12F steel as-received.

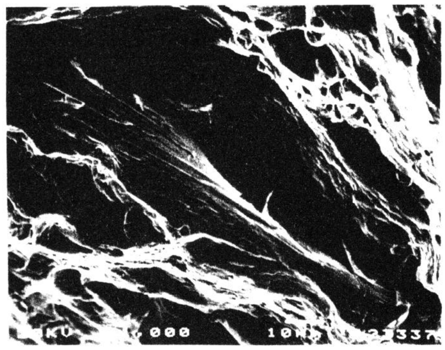

Figure 3b. Fractography of 12F steel aged 14000 hours at 350°C.

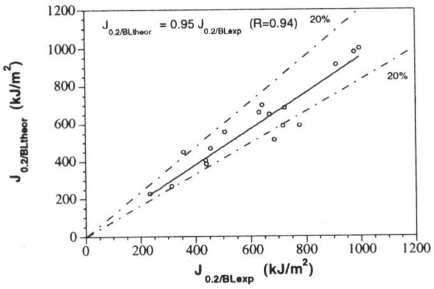

Figure 4a. Relation between $J_{0.2/BLtheor}$ and $J_{0.2/BLexp}$ for the three steels.

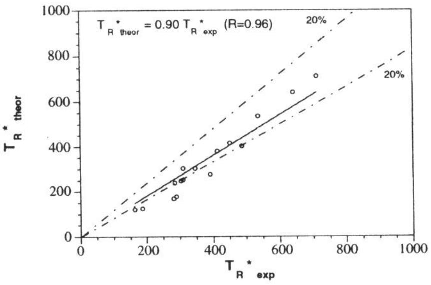

Figure 4b. Relation between $T_R{}^*{}_{theor}$ and $T_R{}^*{}_{exp}$ for the three steels.

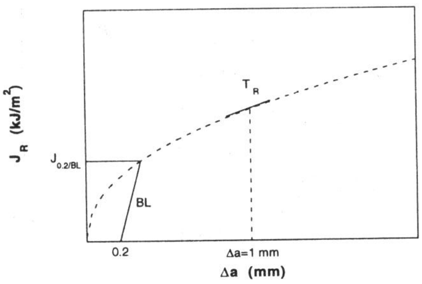

Figure 5. Characteristic parameters of the J_R curve.

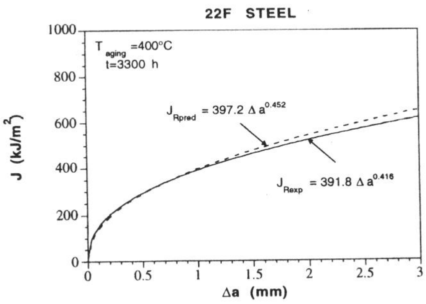

Figure 6. Predicted and experimental J_R curve for the aged 22F steel.