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BEHAVIOR PREDICTION IN THE DUCTILE-TO-BRITTLE TRANSITION PART II: CLEAVAGE STRESS ESTIMATION

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ABSTRACT

In part I of this work some of the methods used to characterize the ductile-to-brittle transition region, in ferritic steels, were discussed, such as the three-parameter Weibull probability, the constraint analysis, and the methodology to predict the behavior in the transition using the two-parameter J-Q theory. In order to apply this methodology it is necessary to know the material cleavage stress. This cleavage stress is not a usually measured property.

A new application for this methodology is presented in this work: how to predict the cleavage stress from the results usually obtained from fracture mechanics experiments, such as J or K for cleavage. The approach was applied for the two materials where the cleavage stress already known; the predicted results were very good. The results obtained for two other materials are presented along with a discussion of the interpretation of the results.

I. INTRODUCTION

The fracture toughness of the ferritic steels exhibits a temperature transition region between the lower temperature region (lower shelf), where all fracture are brittle and can be characterized by the parameter K, and an upper temperature region (upper shelf), where all fracture are ductile and the behavior can be well characterized by the J integral parameter.

In this transition the measured toughness K or J values have a large scatterband and the material usually fails due to the combination of the brittle and the ductile fracture modes. In this region there is a strong influence of the specimen geometry and thickness - as discussed briefly in the part I [1] of this work.

Due to these factors (the mixed fracture mode combined with the strong influence of the specimen dimensions) it is not possible to use a single parameter like K or J to characterize the fracture in this transition region. Some models have been proposed to predict brittle failure considering, basically, that the fracture occurs when the stress field, ahead of the crack tip, reaches some critical value at some characteristic distance from the crack tip. But these models do not take into account the influence of the increasing yielding or of the geometry under analysis. Also handling the scatterband remains a problem.

Recently a two-parameter (J-Q) theory was developed to account for the level of constraint (Q factor) in a fracture toughness determination [3-5]. This factor Q can be seen as the difference between the actual crack tip stress field and that one computed with the small scale yielding (SSY) condition hypothesis.

A model was proposed (briefly reviewed in [1]), based on the J-Q theory, to predict the fracture toughness behavior of cracked bodies and structures in the brittle-to-ductile transition region. The model uses the distribution of the weak link distances from the crack tip to predict fracture toughness. This distribution of the weak link distances is considered a material property and does not change with the temperature. It assumes, also, that the stress field, modified by the Q factor, should reach the material cleavage stress σ_c, at the weak link position ahead of the crack tip, to trigger the failure.

This model, uses a given fracture toughness J_{c1} distribution at a given temperature T_1 and for a geometry G_1, to predict the toughness J_{c2} distribution at another temperature T_2 and/or geometry G_2. It is also possible to predict the end of cleavage (temperature where no more cleavage is possible) for the material.

II. THE CLEAVAGE STRESS PREDICTION

To apply this model one needs to know J_{c1}, T_1, G_1, and the T_2 and G_2 (for which the J_{c2} prediction will be made) and the σ_{ys} yielding (or the σ_o flow) stress at T_1 and T_2, in addition to the material cleavage stress σ_c. The constraint Q factor as function of the loading and the geometry must also be known, to take into account the constraint level in the specimen (or structure).

This model is presented in detail in [2] along with some predictions for cases (geometry and temperature) where the target values (J_{c2}) are known, with very good results. However, to apply the model of the cleavage stress, must also be known. In this work the cleavage stress was available for only two materials: a 20MnMoNi55 steel [7] and a CrMoV steel [8].

Using the model it is possible to obtain this cleavage stress, for a given material, from the usual fracture results (J_c or K_c for cleavage). For this calculation two J_{c1} and J_{c2} toughness distributions must be known in the transition region for a given material and geometry, at two different temperatures T_1 and T_2 respectively.

The basic idea, to obtain the material average σ_c value, is to guess a σ_c value and, using it, predict the J_{c2p} values from the J_{c1} ones. When the predicted J_{c2p} value matches the target J_{c2} within a given tolerance the actual σ_c value is known: it is the guessed value. Fig. 1 shows the rationale for this application. This is an iterative process where the convergence is defined by the given tolerance.

Immediately a problem arises: which value should be taken at the Jc1 distribution and which one should be considered the target one, in the J_{c2} distribution? It seems consistent to consider the extremes of the distributions as good values for this prediction.

To improve this basic idea it is advisable to have a good set of Jc values at each temperature to be sure that the minimum and the maximum values are near the actual ones (for each of the two temperatures). To comply with this, and to be consistent with [6], at least six values should be available at each temperature.

Another possibility is to use the median values for each distribution (the values associated with a 50% probability). To do this the Weibull three-parameter statistics should be used together with the probability distribution adopted in [6].

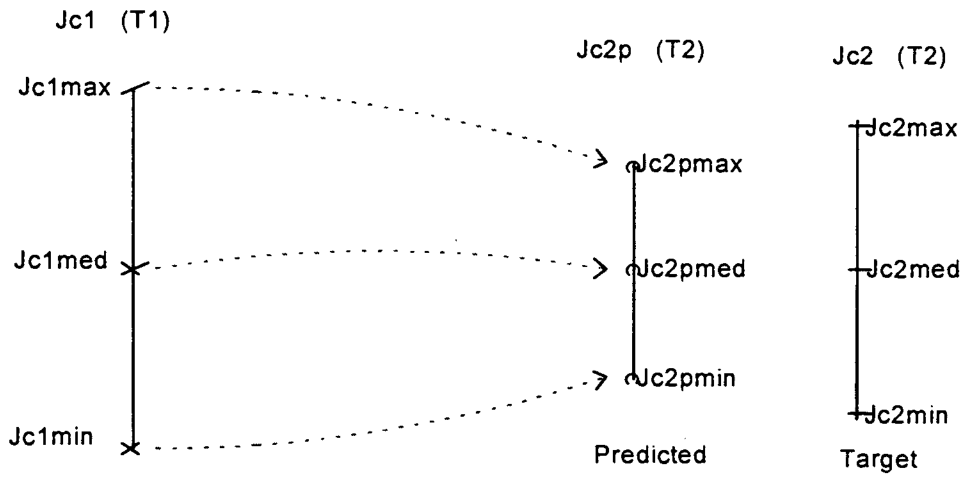

Figure 1. Scheme for the Cleavage Stress Prediction

When applying this methodology to predict σ_c some problems may arise: a) there is more than one σ_c value for which there is convergence within the given tolerance; b) there is no convergence at all.

For the first problem it is suggested that the medium value of the converged σ_c range values be used (the justification will be shown in the next section). The second problem will also be in the next section. The basic approach is to look at the behavior of the predicted J_{c2} values versus the guessed σ_c ones.

In the next section some predictions will be presented (using available data sets) for the two materials with already known σ_c values, along with a discussion about the convergence of the process.

III. TEST APPLICATION - 20MnMoNi55 AND CrMoV STEELS

The cleavage stress had been measured separately for two materials: a 20MnMoNi55 steel and a CrMoV steel. The medium value of cleavage stress is 1750 MPa [7] and 1900 MPa [8] respectively.

The methodology previously presented in this paper was initially applied for these two steels using the data from [1]. For the 20MnMoNi55 the values for the CT specimen data with b=20mm and w=50mm, a/w=0.5, at -60 °C (12 values) and at -90 °C (22 values) were used. For the CrMoV the values for the CCT specimen with b=10mm, w=20mm at 20 °C (16 values), 80 °C (13 values) and at 100 °C (11 values) were used.

Some of the results, in terms of the predicted σ_c, are presented in table 1 (20MnMoNi55) and in table 2 (CrMoV) and in fig. 1-3. For the first material a value of $\sigma_c \approx 1600$ MPa was found, while for the second: $\sigma c \approx 2000$ Mpa was found. Comparing with the target medium values there is about 9% and 5 % of difference. Considering the scatter in the data, from which the medium σ_c values were obtained, these differences are acceptable.

Discussion. As can be seen for some values in the column "From Converged Values", of the table 1, and for all values in table 2, there was no convergence (the difference between the predicted value and the target one is greater than the given tolerance). In the case of the 20MnMoNi55 this is not a strong drawback due to the other converged values from which one can obtain the medium σ_c desired value, but it is for the CrMoV once there was no convergence at all (the tolerance was set as 20% of the target value).

However, when the predicted J_{c2} values were plotted against the guessed σ_c values (see, as examples, fig. 2 to 4) a clear behavior can be observed: the curves show a maximum (if $T_1 < T_2$) or a minimum (if $T_1 > T_2$). When there is convergence this minimum (maximum) occur around the position of the medium σ_c converged value. For those cases where no convergence was achieved it can be verified that the minimum (maximum) occur near the position of the known value of σ_c.

TABLE 1. Predicted σ_c Values. 20MnMoNi55 Steel (MPa)

	from T_1 = -60. °C to T_2 = -90. °C			
Jc minimum	no convergence	σc medium ≈ 1550.	$\sigma_c \approx 1750.$	σ_c medium ≈ 1620.
Jc median	$1300 \le \sigma_c \le 1800$		$\sigma_c \approx 1600.$	
Jc maximum	$1300 \le \sigma_c \le 1800$		$\sigma_c \approx 1500.$	
	from T_1 = -90. °C to T_2 = -60. °C			
Jc minimum	no convergence	σc medium ≈ 1675.	$\sigma_c \approx 1780.$	σ_c medium ≈ 1580.
Jc median	$1300 \le \sigma_c \le 1800$		$\sigma_c \approx 1580.$	
Jc maximum	$\sigma_c \approx 1800$		$\sigma_c \approx 1380.$	
	From Converged Values		From the Max / Min	

TABLE 2. Predicted σ_c Values. CrMoV Steel (MPa)

	from T_1 = 80. °C to T_2 = 100. °C			
Jc minimum	no convergence	no σ_c medium	$\sigma_c \approx 2180.$	σ_c medium ≈ 2110.
Jc median	no convergence		$\sigma_c \approx 2180.$	
Jc maximum	no convergence		$\sigma_c \approx 1980.$	
	from T_1 = 80. °C to T_2 = 20. °C			
Jc minimum	no convergence	no σ_c medium	$\sigma_c \approx 2080.$	σ_c medium ≈ 1980.
Jc median	no convergence		$\sigma_c \approx 1980.$	
Jc maximum	no convergence		$\sigma_c \approx 1880.$	
	from T_1 = 100. °C to T_2 = 20. °C			
Jc minimum	no convergence	no σ_c medium	$\sigma_c \approx 2160.$	σ_c medium ≈ 1990.
Jc median	no convergence		$\sigma_c \approx 1960.$	
Jc maximum	no convergence		$\sigma c \approx 1860.$	
	from T_1 = 100. °C to T_2 = 80. °C			
Jc minimum	no convergence	no σ_c medium	$\sigma_c \approx 2060.$	σ_c medium ≈ 1925.
Jc median	no convergence		$\sigma_c \approx 1860.$	
Jc maximum	no convergence		$\sigma_c \approx 1860.$	
	From Converged values		From the Max / Min	

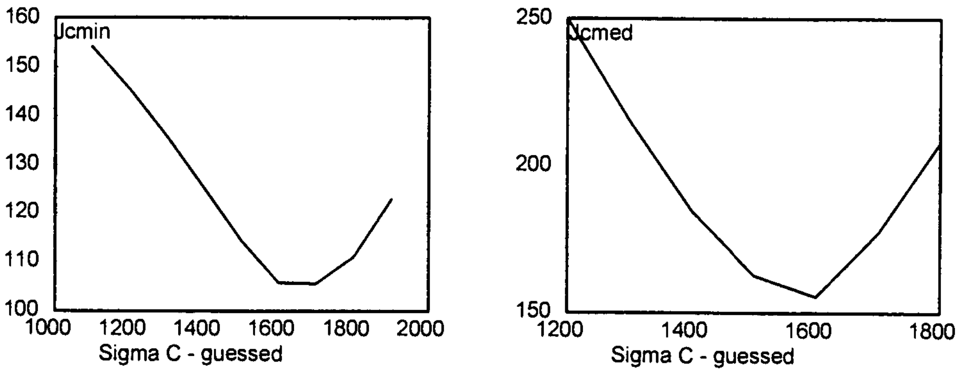

Figure 2. σ_c Prediction for the 20MnMoNi55 Steel - T_1 = -60 °C, T_2 = -90 °C

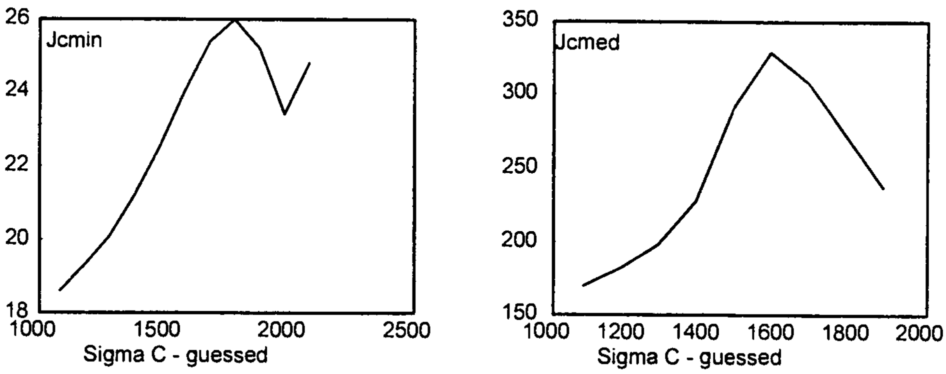

Figure 3. σ_c Prediction for the 20MnMoNi55 Steel - T_1=-90 °C, T_2=-60 °C)

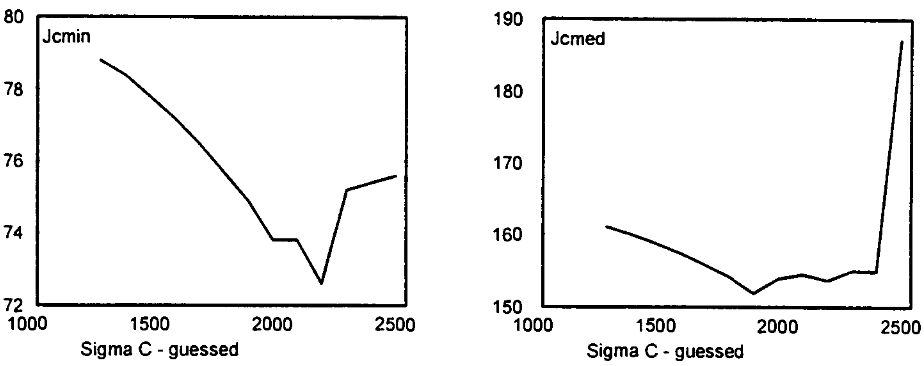

Figure 4. σ_c Prediction for the CrMoV Steel - T_1=100 °C, T_2=80 °C

So, it is possible to obtain the desired medium cleavage stress value applying the methodology to predict the behavior in the transition region, from the described basic idea, even if there is no convergence in the process, using the behavior of the curve "J_c predicted" X "σ_c guessed" (the desired σ_c value will be near the maximum or minimum of this curve).

IV. APPLICATION FOR NEW MATERIALS: A508 and A533B STEELS

After it had been established that the model worked well, it was used to obtain the cleavage stress for two other materials: an A508 steel and an A533B steel labeled, respectively, as "JSPS/MPC" and "McCabe's Data" in [9].

For the first material the data were taken at -50 °C (20 values), -75 °C (20 values), -100 °C (15 values) and for the second one at -18 °C (6 values), -75 °C (26 values).

Some of the results found for these two materiais are presented in table 3, in fig. 6 and 7 (A508) and in fig. 8 (A533B). The predicted medium σ_c values are, respectively, 1600 MPa and 1580 MPa.

TABLE 3. Predicted σ_c Values. A508 and A533B Steels (MPa)

		Cleavage Stress σ_c (MPa) from			
T_1 (°C)	T_2 (°C)	convergence	min / max	σ_c medium	material
-50	-100	1540.	1640.		
-100	-50	1530.	1665.	1600.	A508
-75	-50	1530.	1580.	(MPa)	(JSPS-MPC)
-75	-100	1650.	1665.		
-18	-75	1540	1600	1580	A533B
-75	-18	1580	1610	(MPa)	(McCabe's)

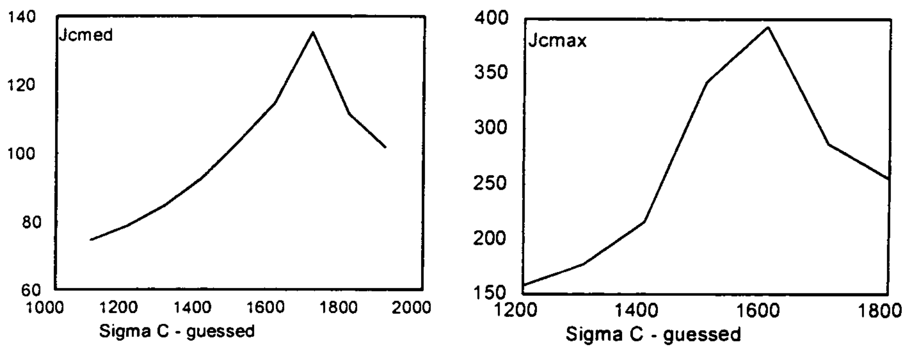

Figure 6. σ_c Prediction for the A508 Steel - T_1=-100 °C, T_2=-50 °C

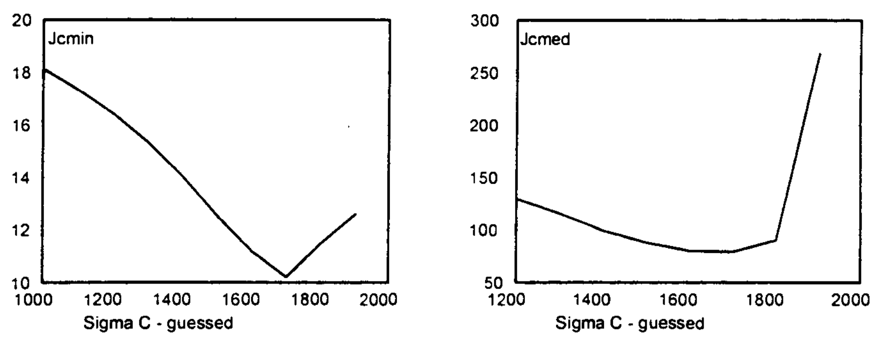

Figure 7. σ_c Prediction for the A508 Steel - T_1=-50 °C, T_2=-100 °C

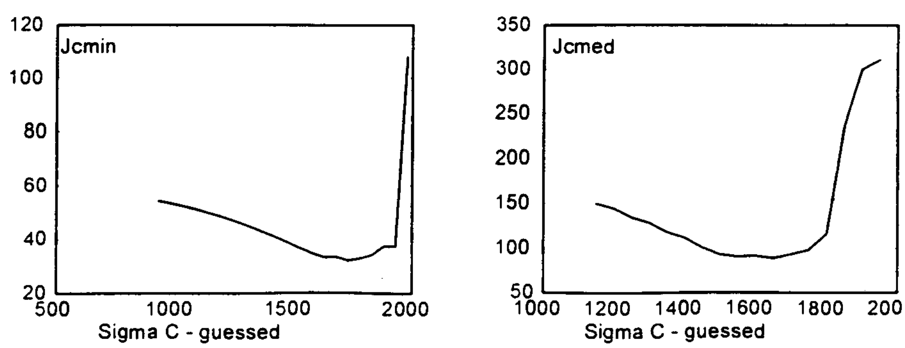

Figure 8. σ_c Prediction for the A533B Steel - T_1=-18 °C, T_2=-75 °C

V. CONCLUSION

In this paper a methodology was presented to obtain the cleavage stress for a given material from fracture mechanics toughness measurements, Jc or Kc for cleavage. The predictions for two materials (20MnMoNi55 and CrMoV steels) with previously known cleavage stress show good results with an error < 10%.

The methodology was applied for two other materials (A533B and A508 steels). The medium cleavage stress values found are 1580 MPa and 1600 MPa respectively.

Some discussions about the convergence of the process were, also, addressed.

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