FATIGUE PROPAGATION OF LONG CRACKS IN METASTABLE AUSTENITIC STAINLESS STEELS

D.F. Martelo[1)], A. Mateo[2)], G. Fargas[2)] and M.D. Chapetti[1)]

[1)]Laboratory of Experimental Mechanics (LABMEX) Research Institute for Material Science (INTEMA) CONICET - Faculty of Engineering, National University of Mar del Plata J.B. Justo 4302, 7600 Mar del Plata, Argentina
[2)]CIEFMA - Departamento de Ciencia de Materiales e Ingeniería Metalúrgica, Universitat Politècnica de Catalunya, Avda. Diagonal 647, 08028 Barcelona, Spain.

ABSTRACT

Fatigue crack growth of a metastable austenitic stainless steel was investigated in thin specimen under positive stress ratio. Annealed and Cold rolled conditions were used to test the influence of the microstructure. The influence of load ratio and load history on propagation behavior was analyzed using the Elber`s closure approach, the Donald and Paris partial crack closure and the empirical Kujawski $(\Delta K \bullet Kmax)^{\alpha}$ parameter. Results show that load ratio effects could be explained by two parameters concepts. It seems that the amount of martensite transformation is responsible for the observed differences in fatigue crack growth resistance.

KEYWORDS

Fatigue crack propagation, metastable austenitic stainless steel, crack closure

INTRODUCTION

AISI 301LN stainless steel is one of the materials that fulfill the exigencies of the automotive sector for the development of components that can be used to lead to weight reductions [1]. However, the use of thin walled light components requires an approach to fatigue design much more conservative that the one based on the cyclic stress range ΔS, like the one based on fracture mechanics.

Another important feature that has to be into account in the fatigue design of components made of metastable austenitic stainless steel is related with the microstructural aspects. In the annealed state the AISI 301LN have an austenitic structure which confers them an excellent ductility, while in the cold rolled state, the martensitic transformation that this steel suffer cause an increase of yield stress, with a decrease of the ductility.

In the past, several studies have been conducted on fatigue behavior of metastable austenitic stainless steel [2-7], and the studies realized in high cycle fatigue (HCF) regime have been focused on the influence of martensitic transformation in the FCGR. However, only few studies have been dedicated to the relationship between martensitic transformation, FCGR and mechanical variables like load ratio [5], stress level [6] and load history [7].

In the presented work the influence of microstructure on fatigue crack growth behavior was evaluated in annealed and cold rolled austenitic stainless steels in thin specimen under positive stress ratio. The influence of load ratio on propagation behavior was analyzed by using the Elber`s closure approach, the Donald and Paris partial crack closure approach and the empirical Kujawski $(\Delta K \bullet K_{max})^{\alpha}$ parameter. The results analyzed using this macroscopic parameters look to indicate that martensitic transformation is the key to find an unique relationship between fatigue crack propagation rate and applied driving force in this kind of steel, and that the driving force must take into account at least two independent parameters.

SPECIMEN, MATERIAL AND TESTING

The material utilized in the current study was an austenitic stainless steel AISI 301LN provided by OCAS NV, Arcelor-Mittal R&D Industry Gent (Belgium). The chemical composition of this material is shown in table I. The microstructure of the material is shown in Fig. 1 in cold rolled and in annealed state.

	FE	Cr	Ni	Mo	C	Si	P	S	Mn	Cu
Annealed	bal	17.94	6.30	0.18	0.016	0.513	0.032	0.005	1.481	0.135
Cold Rolled	bal	17.86	6.42	0.24	0.015	0.471	0.031	0.007	1.495	0.173

Table 1: Chemical Composition

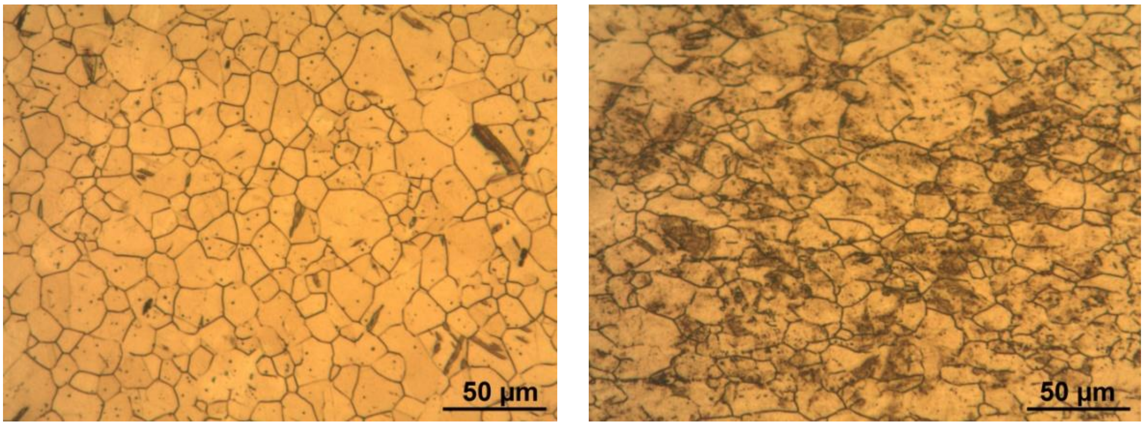


Fig.1: Microstructure of 301 LN stainless steel in annealed (left) and after cold rolling (right).

	σ_{ys}	σ_{UTS}	Elongation (Pct)	Ms (^oC)	M_{d30} (^oC)	M_d (^oC)
Annealed	343 MPa	973 MPa	39,39	-66.015	49.042	100*
Cold Rolled	926 MPa	1113 MPa	24	-66.015	49.042	100*

*For AISI 301 stainless steel.

Table 2: Mechanical and thermo-mechanical properties

Fatigue crack growth rate test were carried out with SENT specimens with two different thickness (1 mm and 1.5 mm), and two width (35 mm and 40 mm). The specimens were machined with the rolling direction parallel (T-L) and perpendicular (L-T) to the notch. The fatigue tests were performed at a frequency of 20 Hz. Three different values of load ratio R ($\sigma_{min}/\sigma_{max}$ = 0.1, 0.3, 0.5), and different stress levels for the same load ratio were employed.

The FCGR test were conducted in an Instron's servo-hydraulic machine with closed loop to computers for automatic test control and data acquisition. The crack extension was measured with a krak-gages® technique [8]. The crack extension was also measured using the compliance technique by means of a clip gage in the crack mouth. The crack closure measurement were made by using a sampling rate of 400 data pairs (load and displacement) per cycle according to some of the recommendations made by Song et al [9].

For the specimen type used in this investigation and for the grid constraint of our test's machine, the stress intensity factor for the specimen of this investigation is not tabulated in books, therefore the finite element method (FEM) was employed to obtain the value of the stress intensity factor. Figure 2 shows the ΔK solutions used for the two configurations that have been used for test and the typical solution available in literature for SENT.

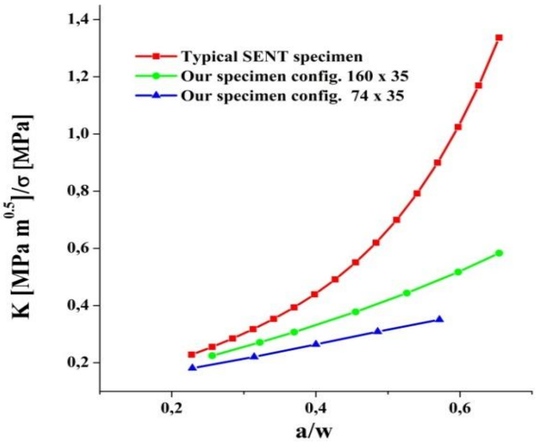


Fig 2: Stress intensity factor obtained by finite element models for the used configurations.

EXPERIMENTAL RESULTS

Results using the range of the stress intensity factor

Fig 3 shows the results of fatigue crack growth experiments in an AISI 301LN at room temperature, at 3 different load ratios, different load levels in annealed (a) and cold rolled state (b), in different crack plane orientations. The results show that the influence of load level and crack plane orientation is negligible, in spite of it found some papers that mention that this aspects are important in fatigue crack growth behavior [6,7]. If the FCGR at the same range of stress intensity factor and the same load ratio are compared, it can be seen that the austenitic stainless steel in annealed condition has a lower FCGR than the FCGR in cold rolled state. For example, to a range of stress intensity factor of about ΔK = 20 MPa√m, the crack propagates between three and five times faster in the cold rolled condition than in the annealed one, depending on the load ratio.

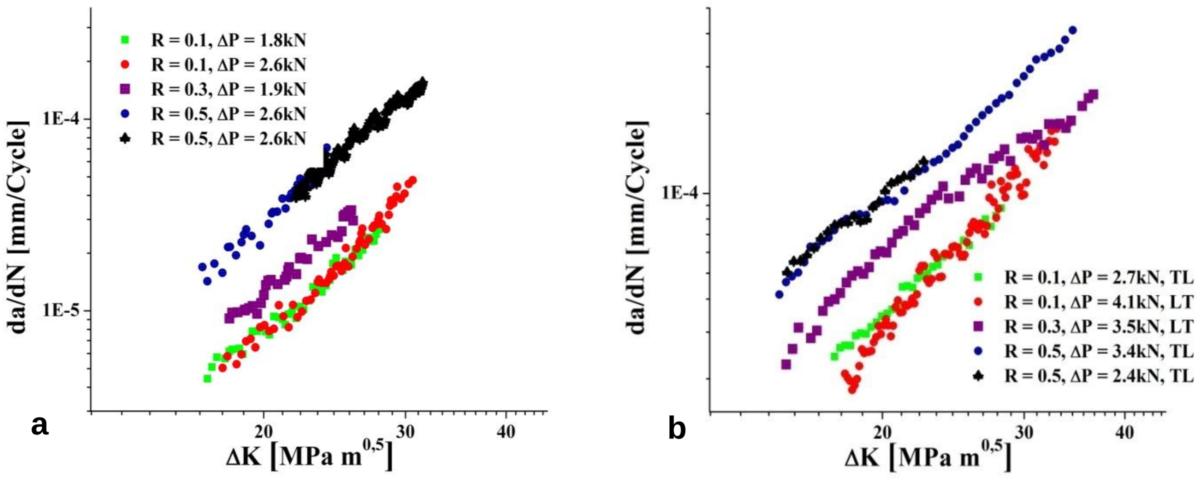


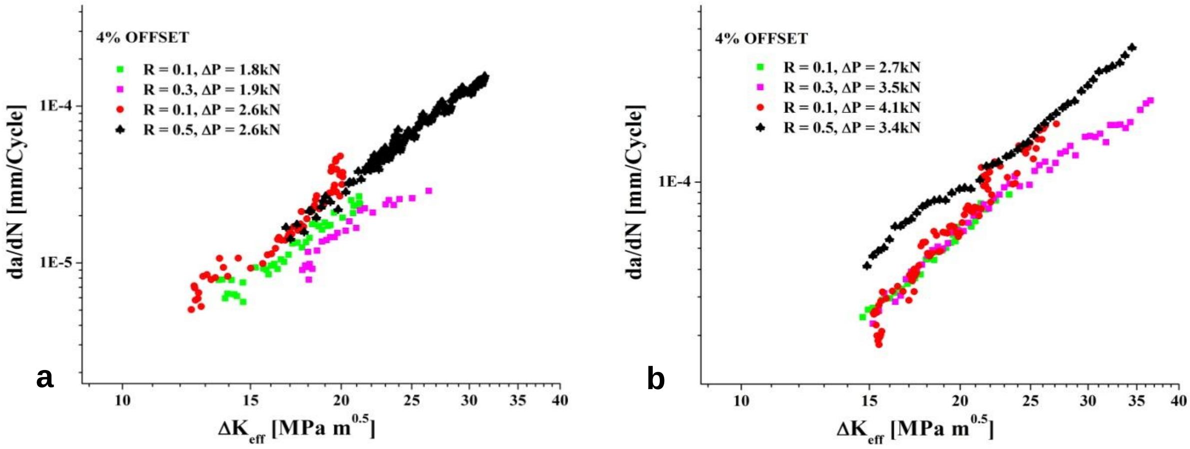
Fig 3: Fatigue crack growth rate vs stress intensity factor range at different load ratios in the stable crack propagation region (a) for annealed and (b) cold rolled condition.

Results using the effective stress intensity factor

The fatigue crack growth rate was plotted also by using the conventional Elber's approach which defines the effective stress intensity range as:

$$\Delta \boldsymbol{K_{eff}} = \boldsymbol{K_{max}} - \boldsymbol{K_{op}} \tag{1}$$

Fig 4 shows the obtained results using the ΔK_{eff} proposed by Elber, with an offset criterion of 4% (This offset criterion provides a more physical meaning of driving force, and this analysis will be detailed in a paper that will be soon submitted for publication). For the configuration analyzed in this work (annealed specimen of 1mm thickness and cold rolled specimen of 1.5 mm thickness), the crack closure is only important at low load ratio (R = 0.1 and 0.3 for annealed condition and 0.1 for cold rolled condition). The test carried out at R = 0.5 for the annealed condition and R = 0.3 and R = 0.5 for the cold rolled condition are free of crack closure.



<u>Fig 4:</u> Fatigue crack growth rate as a function of the effective stress intensity factor (a) for annealed and (b) cold rolled condition.

Results using the Donald`s effect

Considering that the interference of crack surfaces do not completely shield the crack tip form fatigue damage [10], K. Donald and P. Paris has proposed to calculate an effective stress intensity factor range as:

$$\Delta \boldsymbol{K_{2/PI}} = \Delta \boldsymbol{K_{app}} - \frac{\boldsymbol{2}}{\boldsymbol{\pi}}\left(\boldsymbol{K_{op}} - \boldsymbol{K_{min}}\right) \tag{2}$$

Although this method has provided successful correlation of the crack growth rate data for aluminum alloys, does not provide a better correlation of the R-ratio effects than the traditional ΔK_{eff} calculated by Elber`s concept, as shown in Fig 5. Even the approaches based in the crack closure tend to reduce the difference in FCGR between annealed and cold rolled condition, the crack closure cannot explain the observed differences in FCGR.

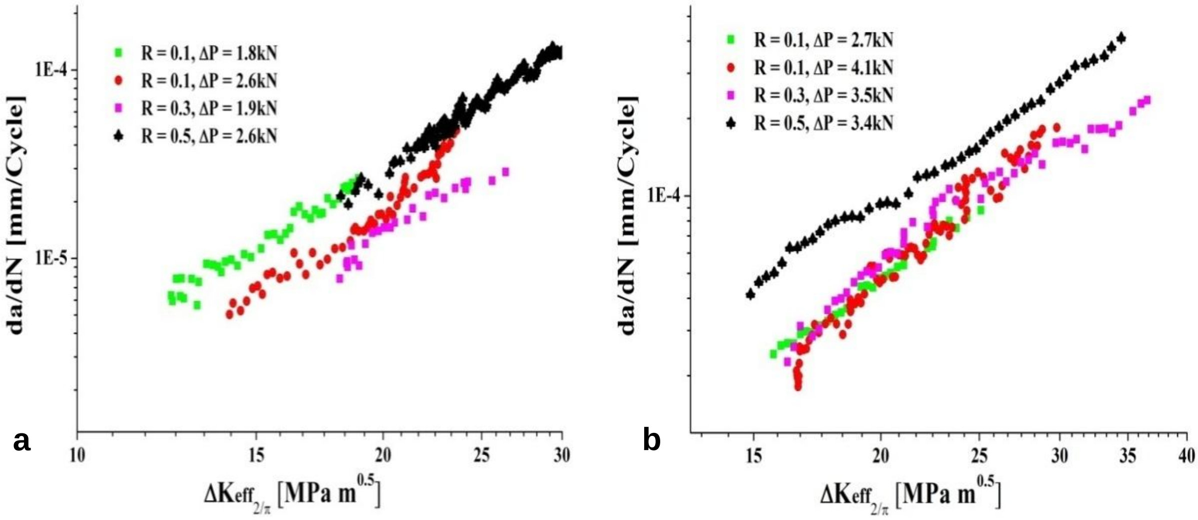


Fig 5: Fatigue crack growth rate as a function of the effective stress intensity factor proposed by Donald et al in the stable crack propagation region in (a) annealed and (b) cold rolled state.

Results using the Kujawski`s Parameter

To describe uniquely a fatigue behavior, it should be necessary to use two independent loading parameters, which could be σ_{max}, σ_{min}, $\Delta\sigma$ or R, or (by using LEFM parameters) K_{max}, K_{min}, ΔK or R. The contributions of these parameters to fatigue crack depend on the material properties and the test conditions. To have into account the effect of mean stress and because of there is no agreement among research with respect to the real damage associate to a crack partially open, D. Kujawski proposed a crack driving force parameter that is calculated by using K_{max} and ΔK as follows [11]:

$$\boldsymbol{K}^* = (\boldsymbol{K}_{\boldsymbol{max}})^{\boldsymbol{\alpha}}(\Delta\boldsymbol{K})^{\mathbf{1}-\boldsymbol{\alpha}} \tag{3}$$

In which α is an empirical parameter that determines the importance of ΔK and K_{max} on the driving force. The average α value found for the AISI 301LN in the annealed condition was 0.6, while in the cold rolled condition was 0.7. Fig 6 shows the results using this parameter.

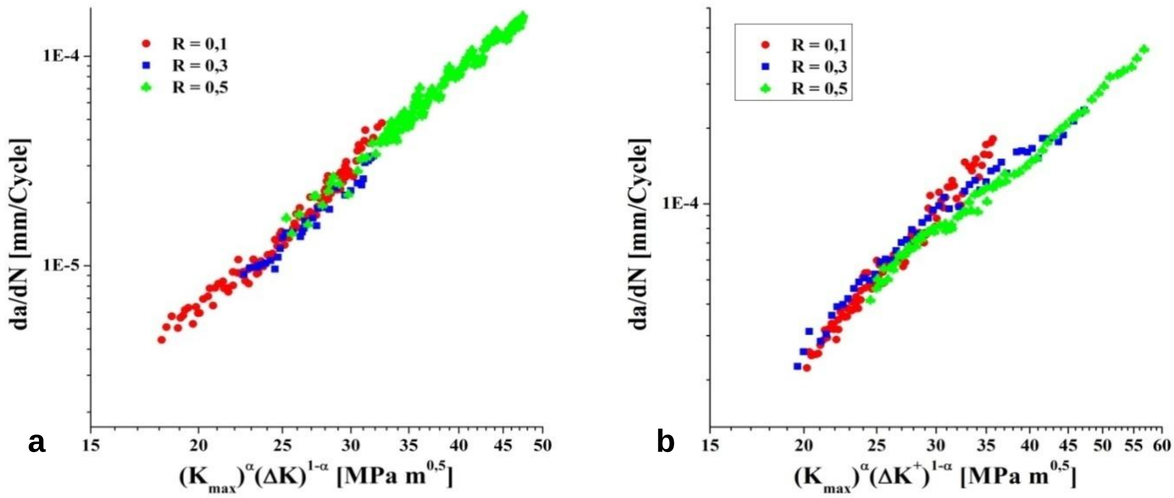


Fig 6: Fatigue crack growth rate as a function of the Kujawski`s parameter with (a) α equal to 0.6 in the annealed condition and (b) α equal to 0.7 for the cold rolled condition.

CONCLUDING REMARKS

The fatigue crack growth behavior of an austenitic stainless steel AISI 301LN was analyzed on two different microstructural conditions and different load ratios. It was attempted to explain the effect on FCGR of those different variables using traditional approaches based on crack closure and the two driving force concepts.

The explanation based on crack closure by using the Elber parameter or the Donald and Paris parameter, even though diminishes the difference in FCGR versus driving force, does not explain satisfactorily the effects of neither of the variable studied in this work.

The kujawski's parameter with different values of α (depending of the microstructural condition), can explain satisfactory the effect of load ratio. However, this is an empirical parameter which is only based on macro mechanical driving force, and it is not formulated to account the difference in microstructural characteristics. It is necessary further investigation in the relationship between crack growth and microstructure, which in this steel is strongly marked by the martensitic transformation.

REFERENCES

[1] Beese, A.M.:
Quantification of Phase Transformation in Stainless Steel 301LN Sheets. Massachussetts Institute of Technology. (2008)

[2] Chanani, G.R.; Antolovich, S.D.; Gerberich, W.W.:
Fatigue Crack Propagation in Trip Steel. Metallurgical Transactions 3A (1972), pp. 2661-1672

[3] Pineau, A.G.; Pelloux, R.M.:
Influence of Strain-induced Martensitic. Transformation on fatigue Crack Growth rates in Stainless Steels. Metallurgical Transactions 5 (1974), pp. 1103-1112

[4] Hornbogen, E.:
Martensitic Transformation at a Propagating Crack Acta Metallurgica 26 (1978), pp. 147-152

[5] Mei, Z.; Morris Jr, J.W.:
Influence of deformation-induced martensite on fatigue crack propagation in 304-type steels. Metallurgical transactions A 21A (1990), pp. 3137-3152

[6] Schuster, G.; Altstetter, C.:
Fatigue of Annealed and Cold Worked Stable and Unstable Stainless Steels. Metallurgical Transactions A 14 (1983), pp. 2077-2084

[7] Biswas, S.; Sivaprasad, S.; Narasaiah, N; Tarafder, S; Chakraborti, P.C.:
Load history effects on FCGR behaviour of 304LN Stainless Steel. Int. Journal of Fatigue 29 (2007), pp. 786-791

[8] TTI Division, Hartrun Corporation. Krak-gage Accuracy and Resolution
Chaska Minessota (1981) KRAK TIP No. 8109-1

[9] Song, J.H; Chung, Y.I.:
Improvement of ASTM compliance offset method for precise determination of crack opening load. Int. Journal of Fatigue 31 (2009), pp. 809-819

[10] Paris, P.; Tada, H.; Donald, J.K.:
Service load fatigue damage - a historical perspective. Int. Journal of Fatigue 21 (1999), pp. S35-S46

[11] Kujawski, D.:
A fatigue crack driving force parameter with load ratio effects. Int. Journal of Fatigue 23 (2001), pp. S239-S226

Corresponding author: mchapetti@fi.mdp.edu.ar