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Evaluation of the impact of residual stresses in crack initiation with the application of the Crack Compliance Method Part II, Experimental analysis

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Abstract. The present work is based on a previous numerical simulation used for the introduction of a residual stress field in a modified compact tensile specimen. The main objective in that paper was to evaluate the effect that previous history has in crack initiation and to establish the new loading conditions needed to propagate a fracture. The experimental analysis presented in this paper was performed to compare and validate the numerical procedure. Several modified compact tensile specimens from a biocompatible material (*AISI 316L*) were manufactured to estimate the beneficial effect of a residual stress field. The specimens were separated in four batches; an initial group of uncracked specimens was used to establish an evaluation of the induction of a residual stress field produced by an overload; the remaining specimens were separated into three groups where a crack was introduced in each specimen (1 mm, 5 mm and 10 mm respectively) and the residual stress field caused by the application of an overload was determined. The assessment of all the residual stress fields introduced into the specimens was done by the application of the crack compliance method (*CCM*). The results obtained have provided useful information on the correlation between the numerical and experimental procedures. Furthermore, data concerning the understanding of diverse factors related to crack initiation are discussed in this paper. Finally, the beneficial aspects of the residual stresses are discussed.

Introduction

Probably one of the most complicated problems that a mechanical engineer or scientific researcher could face is the assessment of crack propagation in components with previous loading history. It is a fact, that residual stresses have been studied as a mechanical procedure to enhance the mechanical resistance of the material after the application of a manufacturing process. On the other hand, not enough effort has been drawn to investigate how a beneficial residual stress field could act after a crack has been activated by a loading procedure.

Additionally, in recent years there has been a growing interest in crack arrest problems. It has been well documented and recognized that in order to predict arrest of cracks, it is necessary a clear description of the crack growth preceding arrest [1-2]. Maybe, the principal inconvenient regarding this kind of investigation, is that most of the work done in this field has been based on the assumption of linear elastic fracture mechanics (*LEFM*); that is, the state at the crack tip is assumed to be characterized usually by the stress intensity factor [3]. Apparently the theoretical basis of *LEFM* appears to be sufficient to solve this kind of problems. However, the development of this knowledge is not sufficient to judge whether the linear theory is valid, or, rather, if it provides the desired accuracy level in a certain situation. On the other hand, it becomes more complicated when plasticity theory and previous loading history in the specimen is involved.

The investigation presented in this paper is aimed to establish the effect of prior loading history in the development of a crack and how a beneficial residual stress field could increase the mechanical resistance of the material. This paper corroborates by an experimental procedure the numerical study presented in part I of this research.

Material and test specimen

The material used in this work is stainless steel *AISI 316L*, which is one of the most utilized steel in the area of biomechanics. The chemical composition of the stainless steel *AISI 316L* is presented in Table 1 [4].

Table 1.- Chemical composition stainless steel *AISI 316L*

Element	C	Mn	Si	Cr	Ni	P	S	Mo
Weight (%)	0.03	2.0	1.0	16-18	10-14	0.045	0.03	2-3

The experimental development of this research has been performed in a keyhole specimen, which is a modification of a compact tension specimen per ASTM standard E 647-91 with special requirements as indicated in ASTM E 399 [5] (Fig. 1).

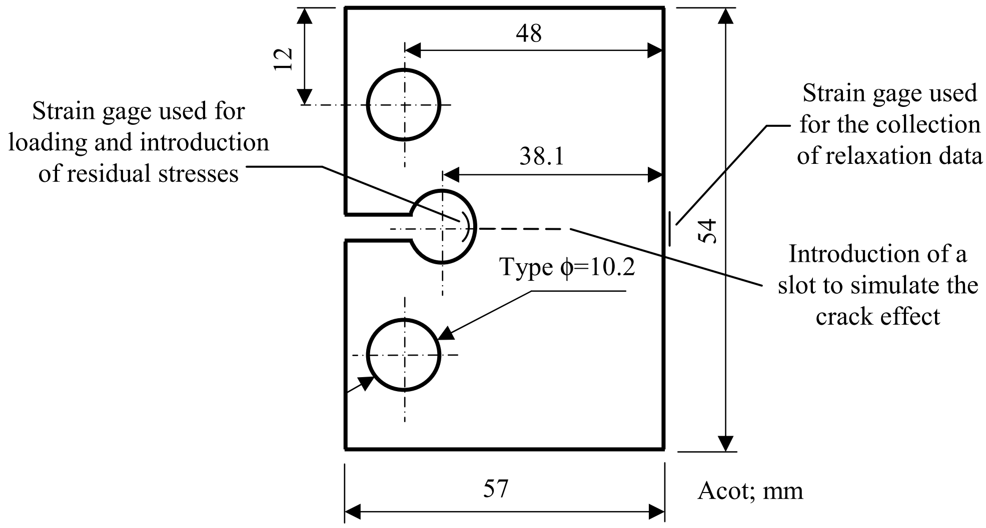

Figure 1.- Modified compact tensile specimen SEN

The main reason for the modification of the compact SEN specimen is to ensure (up to certain degree) that the manufacturing process will not produce more cracks or structural defects into the material. The main characteristic on the modification of the specimen is a hole inducted at the notch tip. A set of sixteen specimens were manufactured for this investigation and there were divided into four groups of 4 specimens each. The entire set of specimens was stress release annealed by heat treatment process of 600 ^{o}C for half an hour and slowly cold down inside a furnace [6]. The reason for applying a heat treatment process was to eliminate any kind of prior loading history acting into the material.

In the first case of study, it was included the introduction of a residual stress field into a specimen free of a crack. For the next three cases of study, an analysis was performed to evaluate the effect of an existing crack (with different lengths 1 mm, 5 mm and 10 mm, respectively) and the state of a residual stress field, which will modify the conditions for crack propagation. The generation of the crack into the specimen was performed by a wire electro discharge machine (*EDM*) in a manner as a slot (Fig. 2a). The decision to use the electric discharge machine was to produce a crack and to avoid the introduction of an additional stress field into the material. Additionally, great care was taken to induce a crack that was no thicker than 1 mm for all cases (Fig. 2b).

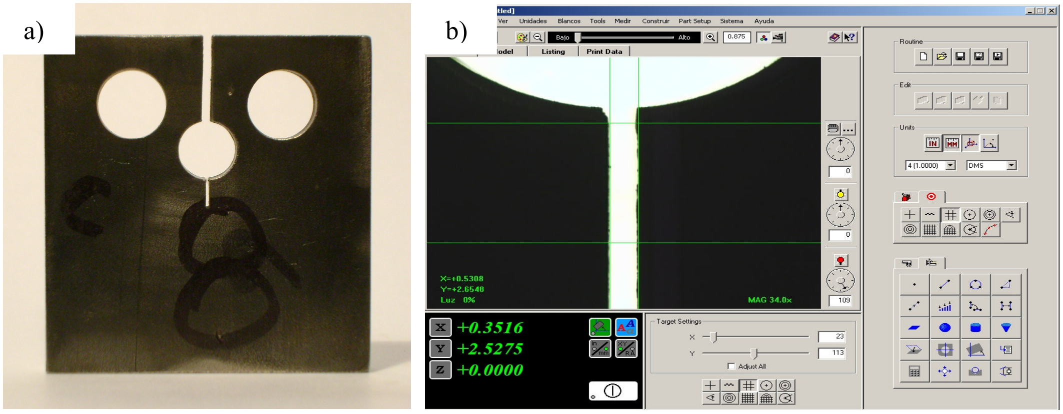

Figure 2.- Cracked modified compact tensile specimen SEN
a) Specimen with a 5 mm slot. b) Slot width evaluation.

Material characterization and preparation of specimen

For the characterization of the stainless steel *AISI 316L*, four beam specimens of 10 mm high by 6.35 mm thick by 250 mm length were prepared [7]. The beams were stress relief annealed to eliminate prior loading history [6]. The stress-strain curve for this material was obtained by four point bending tests (Fig. 3) [8]. The main advantages on this procedure are the simultaneous evaluation of tensile and compress behaviour. The Young´s modulus and Poisson ratio obtained from this tests and used for the application of the *CCM* was 190 MPa and 0.28 respectively.

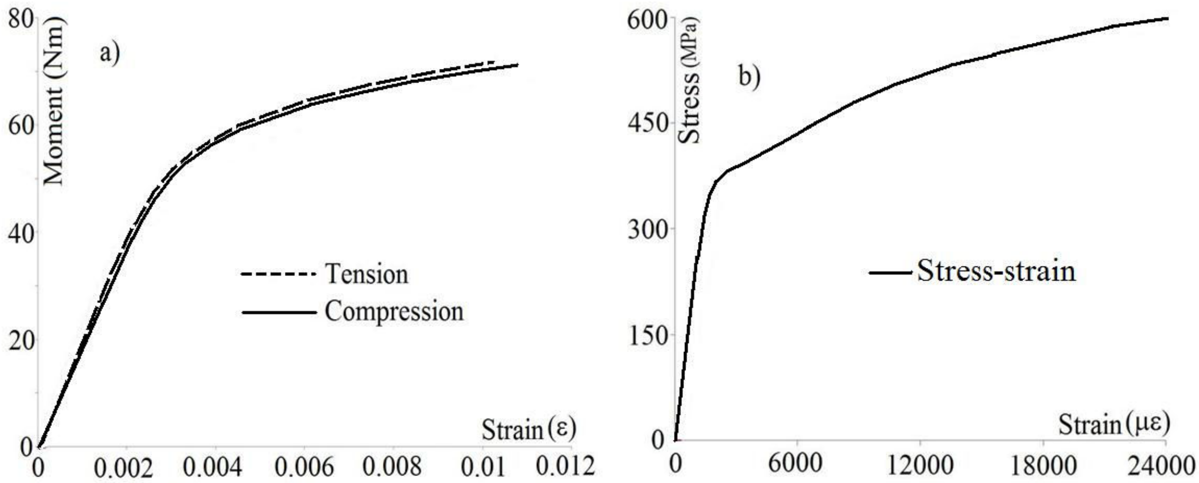

Figure 3.- Mechanical characterization of stainless steel *AISI* 316L
a) Bending test data used to obtain the stress-strain curve. b) *AISI 316L* stress-strain curve.

Experimental introduction of the residual stress field

All the specimens were prepared with a strain gauge at the rear surface (with respect to the concentration stress hole (Fig. 1)). This gauge will be used to measure the strain relaxation caused by the introduction of the slot and to be applied by *CCM* for the evaluation of the residual stress field induced into the material. Additionally, in the specimens free of an initial crack, a strain gauge was applied at the hole´s border (Fig.1) to measure the strain effect related to the application of the tensile load and to correlate the experimental analysis with the numerical evaluation.

In the numerical simulation a 100 N load was distributed in 17 nodes at the loading keyhole (Part I of this study). The resulting numerical strain obtained at the tip of the concentration hole was of 5675 $\mu\varepsilon$ and is the base for the determination of the experimental load, which was found to be 975

N. The load was applied in a tensile form by a servo-hydraulic device, with a capacity of 100 kN and was the same for all the experimental study cases. This magnitude in the load is large enough to produce a localized plasticity effect near the stress concentration zone while elasticity will remain around the specimen, so by unloading the system a residual stress field will be introduced.

Specimen preparation for the application of the crack compliance method

After the induction of the residual stress field was performed in all the study cases, the results obtained in the numerical analysis were used to assess the manner in which the specimen will relax by the introduction of the cut. With this information, it was possible to determine the best way to hold the specimen to perform the cutting and to obtain the strain relaxation for the application of the *CCM*. So, it was decided to clamp the specimen at one of its sides and support it at the other side, as how shown in Fig. 4.

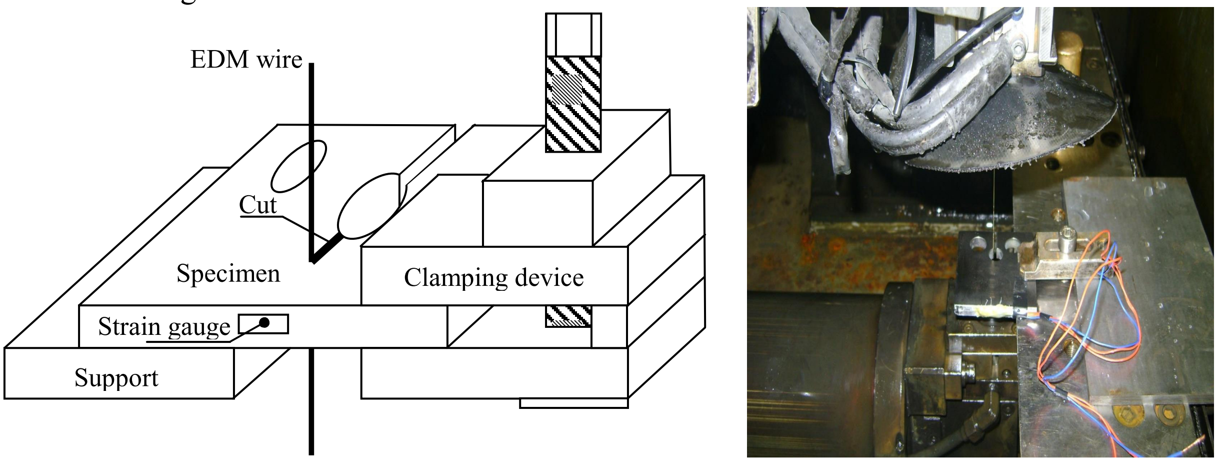

Figure 4.- Representation of the way the specimen is support and cut

The cut was done by a wire *EDM* (CHARMILLES, model ROBOFIL) in sequential steps of 1 mm of length for all cases, and the strain relaxation data was obtained using a Wheatstone bridge configuration. Also, the strain gauges were protected with M-Coat-A Air Drying Polyurethane coating as first stage and finishing with an M-Coat-B Nitride Rubber coating. The use of this procedure is to ensure the encapsulation of the strain gauge when it is submerged into the dielectric liquid used by the *EDM* machine.

Experimental cases of study and results

The theory, application and performance of the *CCM* have been extensively explained by several authors [9-13]. The first experimental case of study is the introduction of a residual stress field into a specimen free of crack. Also this first experimental case was used to set up and evaluate the accuracy of the *CCM*. For the next three experimental cases of study, an analysis was performed in the effect of the introduction of a residual stress field in a specimen with a crack of different length (1 mm, 5 mm and 10 mm, respectively). The results obtained by the application of the *CCM* and also a comparison against the numerical evaluation can be observed in Figure 5.

Conclusions

The validation for the experimental application of the *CCM* on the determination of induced residual stress fields has been presented in this paper. Additionally, in this research it has been proved that the *CCM* can be applied to components other than beams, pipes and regular plates. It has also been establish that the *CCM* can be applied in specimens wider than 10 mm, for example this investigation was applied to material thickness of 23 mm, 28 mm, 32 mm and 33 mm (which represents the specimens with crack lengths of 10 mm, 5 mm, and 1 mm, and the specimen without a crack).

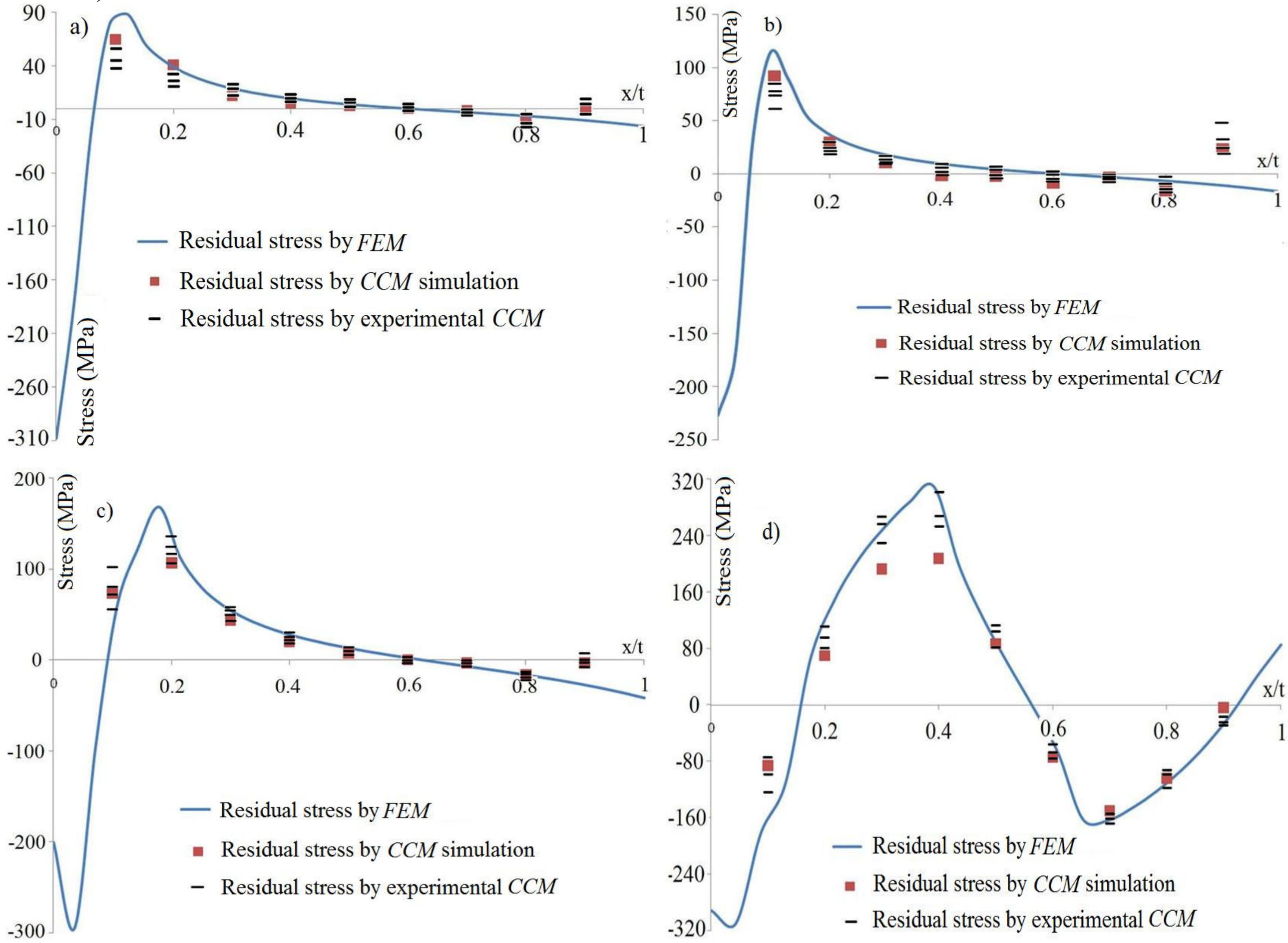

Figure 5.- Residual stress comparison between experimental evaluation against numerical analysis a) Specimen without a crack. b) Specimen with a 1 mm crack long c) Specimen with a 5 mm crack long. d) Specimen with a 10 mm crack long.

The development of a previous numerical analysis, which has simulated the problem applied to this experimental procedure, has provided important and significant data. The numerical study has produced results that were directly applied in the experimental testing and have been useful to simplify the *CCM* procedure. Also, it was very helpful to define the correct manner to hold and support the piece at the moment of the introduction of the slot. Furthermore, the numerical investigation is a powerful tool that has provided the expected results, which later were corroborated by the experimental procedure and have proved that the introduction of a residual stress field could raise the mechanical resistance of the material.

Once again it has been corroborated the importance in the use of the modified compact tensile specimen *SEN*, which has provided a more controllable set up for the introduction of residual stresses and the development of a methodology that effectively arrests the crack propagation. Nevertheless, the main objective in this research was to evaluate the effect of a crack with the introduction of residual stress fields. From Figure 5 it can be concluded that after the effect of the load is removed from specimens with a crack, a beneficial residual stress field has been induced. So, to propagate the crack it will be required more energy than that of the first case, because it has to overcome the residual stress field introduced into the component. On the other hand it can be observed from Figure 5, which there are similar residuals stress fields between both the numerical simulation and the experimental procedure. Nonetheless, it can be observed in Figure 5 that at the ends of the specimen the calculation for the residual stress fields are not as accurate as in the middle part of the specimen. The mismatch at the end opposite to the rear location could be related to the remote position of the effect and the relaxation cannot be read totally at the strain relaxation location. With respect to the discrepancy in residual stress results at the end near to the point of collection of relaxation data, a possible explanation could be based on the fact that the structural integrity has been compromised by the introduction of the cut and only 1 mm of material has been left. It has been corroborated that the combination of loading the crack and removing the load effect has permits the material to gain mechanical resistance. Additionally, it could be said, that a mechanical procedure (like the introduction of a residual stress field) can extend the working life of a component after a crack has been successively loaded and unloaded.

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