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Crack-compliance method for assessing residual stress due to loading/unloading history: Numerical and experimental analysis

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A B S T R A C T

The understanding of how materials fail is still today a fundamental research problem for scientist and engineers. The main concern is the assessment of the necessary conditions to propagate a crack that will eventually lead to failure. Nevertheless, this kind of analysis tends to be more complicated, when a prior loading history in the material is taken into consideration and it will be extremely important to recognize all the factors involved in this process. In this work, a numerical simulation and experimental evaluation of the induction of residual stresses, which change the crack initiation conditions, in a modified compact tensile specimen is presented. Several analyses were carried out; an initial evaluation (numerical and experimental) was performed in a specimen without a crack and this was used for the estimation of a residual stress field produced by an overload; three more cases were simulated and a crack was introduced in each specimen (1 mm, 5 mm and 10 mm long, respectively). The overload was then applied to set up a residual stress field into the component; furthermore, in each case the Crack Compliance Method (CCM) was applied to measure the induced residual stress field. By performing this numerical simulation, the accuracy of the CCM can be evaluated and later corroborated by experimental procedure. On the other hand, elastic–plastic finite element analysis was utilized for the residual stress estimation. The analyses were based on the mechanical properties of a biocompatible material (*AISI 316L*). The obtained results provided significant data about diverse factors, like; the manner in which a residual stress field could modify the crack initiation conditions, the convenient set up for the induction of a beneficial residual stresses field, as well as useful information that can be applied for the experimental implementation in this research. Finally, some beneficial aspects of residual stresses are discussed.

1. Introduction

It is well known worldwide and through the mankind technology development that the application of materials in engineering designs has posed diverse problems [1]. At the beginning of technological development, mankind set its goal to solve the problem of shaping the materials. Latter, the necessity was both the production and shaping of materials. Even so, for many centuries the production and manufacture of diverse components was extremely laborious and costly. Nevertheless, with the passing of time, the improving of technology and skills has allowed a better application of numerous and diverse materials. In particular, the extended increase on the use of metal technology has provided the chance of a faster and better development. However, the use of metals in miscellaneous applications has caused the number of accidents and casualties to reach unknown levels. In these sense there has been abundant fatalities produced by; cars, trains, boats, vessels and airplane failures, construction and structure breakdowns, components poor design, etc. In fact, the main cause of all these accidents has not been entirely due to a poor design, but to a lack of understanding of material deficiencies in a form of pre-existing flaws that tend to nucleate cracks and propagate fractures.

This condition has been gradually corrected by a development and implementation of a new (at that time) science that is called Fracture Mechanics. In this sense, it has been well documented that development of failure could be divided in two basic parts, initiation and spread [2]. Additionally, there is a great number of external and internal factors that contribute to the nucleation and propagation of a crack [3]. Slip bands or dislocations and surface scratches can be considered as internal effects, while as external factors are considered the effect of forces and deformations. Nevertheless, when the development, performance and effect of a crack is analyzed, prior load history in the material is not considered extensively or in a sufficient manner. To consider prior load history in the component raises the difficulty of the problem in a substantial

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way. This is why the simplest way to analyze failure and its consequences is to consider the specimen free of previous load history. But on the other hand, the manufacture of components will always leave inside the material an induced stress or strain field and this field will interact with the development of all sorts of defects [4].

The induction of previous load history into the component is based on the effect leaved by the application of an external agent above the yielding strength of the material when the load is removed. The introduction of previous history can be divided in two great groups; homogenous loading or non-homogenous loading. The consequence of a homogenous loading derives into strain hardening and Bauschinger effect; meanwhile the consequences of non homogeneous loading are the introduction of residual stresses. In both cases, the consequences of the application and removal of the external agent could contribute into the material either in a beneficial and/or a detrimental manner. Strain hardening and Bauschinger effect can be found in the material at the same time, if the component has been strengthen by tensile strain hardening, Bauschinger effect (that is a change of the yield strength value of the material) will be found in the compressive behavior and vice versa. In relation to residual stresses, they are also detrimental and beneficial, as tensile and compressive stresses are applied together and tend to auto-equilibrate them self [5]. So, in the process of manufacturing pieces and components it is very important to identify the outcome that a particular fabrication process could add to the material.

On the other hand, it is very difficult to measure the grade of strain hardening and Bauschinger effect that a material has. It is proposed that the best manner to do it, is to apply a four point bending test in a produced beam specimen of the material in question and compare it to a specimen partially or fully annealed made from the same material [6]. This procedure will provide either an increase in the yield stress produced by the strain hardening procedure or the decrease of the mechanical resistance themselves originated by the Bauschinger effect into the component. In contrast, the quantification of the introduction of a residual stress field in a component can be performed by a great number of methods or techniques. These techniques are divided into three groups; destructive, semi-destructive and non destructive methods. The main difference between each group is related to the structural damage caused to obtain the residual stress field in the component, which in the non-destructive methods the specimen's residual stress field can be acquired and brought back to service, in the semi-destructive techniques the component can be evaluated depending on the technique used to control the damage could be controlled, whilst the destructive procedure completely harms the component making it un-useful for service.

In the group of destructive techniques, there is one procedure that has called the attention of several researchers; this is the Crack Compliance Method (CCM). The name came from the similarity of this technique to the compliance method for measuring crack length in a fatigue or fractured specimen [7]; a known load is applied to a cracked specimen, and the resulting strain is used to determine the crack length (in the CCM the crack length is known and the measured strain is used to calculate the residual stress field acting into the component). In the engineering environment the CCM is also known as; Fracture Mechanics Approach, Successive Cracking Method, Slotting Method, Rectilinear Groove Method, etc. The CCM adds unique new capabilities to the current determination of residual stress measurement procedures. Compared to other destructive methods, this technique offers increased spatial resolution of residual stresses and greater than before sensitivity to low stresses. Additionally, the sub-millimeter spatial resolution provided by the CCM cannot currently be matched by the most common non-destructive techniques (X-ray or neutron diffraction). Other CCM advantages include a simple analytical technique to determine the stress intensity factor caused by a crack in a residual stress field and the ability to measure crack closure stresses. Furthermore, the CCM can be applied fairly easily with commonly available equipment (strain gauges and electric discharge or conventional machining) and it is extremely cheap, when it is compared to other methods [7].

In this paper, it is presented the numerical simulation and experimental evaluation of the introduction of a residual stress field with the objective to modify the strength of the material. Which could improve the mechanical resistance of the component by setting a tensile overload, which at the beginning of its action can propitiate the nucleation or propagation of a crack, but when the application of the external agent is ended it would leave a beneficial residual stress field. Also, in this research paper it is presented a numerical evaluation of the CCM and the determination of the possible residual stress acting on the component. Additionally, it will be corroborated the exactitude of the application of the CCM by an experimental procedure.

2. Theoretical basis of the crack compliance method [5]

The analytical solution using the CCM can be carried out only when the relaxed strain readings have been obtained from cutting a component with inherent residual stresses. In general, the analysis for the determination of the residual stress field from the strain data collected is performed in two stages; the forward solution stage, followed by the inverse solution stage. These solutions are based on linear isotropic material considerations.

In this section a brief summary of the theory relative to the CCM used in this research is presented. Let the unknown residual stress distribution in the beam be represented by the summation of an nth order polynomial series as:

$$\sigma_y(x) = \sum_{i=0}^{n} A_i P_i(x) \tag{1}$$

where A_i are the coefficient that have to be obtained and P_i are a power series, $x^0, x^1, x^2, \ldots x^n$, etc. Legendre polynomials are also used. However, the CCM includes a step which assumes that the stress distribution, $\sigma_y(x) = P_i(x)$, interacting with the crack is known. This known stress field is used to obtain the crack compliance function C by using Castigliano's approach. Therefore, it is required the evaluation of the change in the strain energy due to the presence of the crack and the virtual force. One alternative is by means of the Strain Energy Density. Its main factor, S, is direction sensitive. It establishes the direction of least resistance for crack initiation. The stationary value of $S_{\min}$ can be used as an intrinsic material parameter, whose value at the point of crack instability is independent of crack geometry and loading [8]. In the case of an elastic material, the expression of the intensity of the strain energy density field is:

$$S = a_{11}K_I^2 + 2a_{12}K_I K_{II} + a_{22}K_{II}^2 + a_{33}K_{III}^2 \tag{2}$$

This criterion is based on the local density of the energy field at the crack tip and it is not required any assumption on the direction in which the energy is released. This is suitable for mixed mode loading. For the problem at hand, $K_I = \sigma a^{1/2}$; $K_{II} = K_{III} = 0$, because the specimen is under mode I. In this way, S can be combined with the theorem of Castigliano. The displacement $u(a,s)$ can be determined by taking a derivative with respect to the virtual force, as [9]:

$$u(a,s) = \frac{1}{2}\frac{\partial u}{\partial F}\bigg|_{F-0} = \frac{1}{E'}\int_0^a K_I \frac{\partial K_{IF}(a,s)}{\partial F} da\bigg|_{F=0} \tag{3}$$

Differentiating now with respect to the distance s, the strain in the x-direction is given by [9]: