Determination of Residual Stresses Originated in a Die Process Using the Crack Compliance Method

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***Abstract*— Nowadays, knowledge on the behavior of mechanical components against external agents is important in order to obtain a better understanding about the failure mechanisms that occur during their lifetime. One of the factors to be taken into consideration, on the nucleation and propagation of cracks, is the effect that a previous loading history might have. This is the case of manufacturing processes, which in currently induce residual stresses that alter the nucleation and propagation of cracks. In the present research, residual stress distribution is evaluated in a mechanical component. It is used as a guide in an assault rifle, which is produced by the Mexican army. The material used to manufacture such guide is a 1018 steel, which is subjected to a die process. The characterization of the residual stress field is performed by the use of the Crack Compliance Method (CCM), which is a destructive method. The entire residual stress field, throughout the cross section of a component is evaluated. In order to get a better understanding of the effect of the die process in the induction of the residual stress field, the evaluation of the field is performed considering two directions (horizontal and vertical). The characterization of residual stress field induced by a particular manufacturing process helps us to understand in a more accurate manner the material behavior during its lifetime service.**

***Index Terms*— CCM, Characterization, Crack, Residual stress.**

I. Introduction

Currently, the design of mechanical components has led to the development and implementation of different manufacturing processes, which causes microstructural changes and induce a residual stress field [1], [2]. Such stresses can be beneficial or unfavorable, because they are added to the resultant stresses of the applied loads, increasing its useful life or causing sudden failures [3]. Besides, its greatest effect is on the fatigue life [4]. Regardless the residual stresses, the dimensional stability of the piece is affected, because the material is distorted [5], which leads to imbalances in the machines, causing diverse problems such as vibration, abrasion, temperature rise and others.

The study of residual stress has become very important; in this sense, several measurement techniques have been developed [6]-[8]. One of the most important procedures is the Crack Compliance Method (CCM). It is a destructive technique that is based on the induction of an incrementally crack (cut) in a specimen [9], [10]. In this case, the residual stresses are in static equilibrium. When a cut is introduced into the component, the removed material will produce a rearrangement of the residual stress field, undergoing a strain relaxation. It can be measured by strain gauges in a perpendicular direction with respect of the cut [11]. Also, the CCM is based on Fracture Mechanics theory.

This paper presents the results from the measurement of a residual stress field induced in a mechanical component, made with AISI 1018 steel. This analysis is carried on before and after the manufacture process was performed. The dimensions and geometry of the component is illustrated in Figure 1, as it is received and the end of the die process.

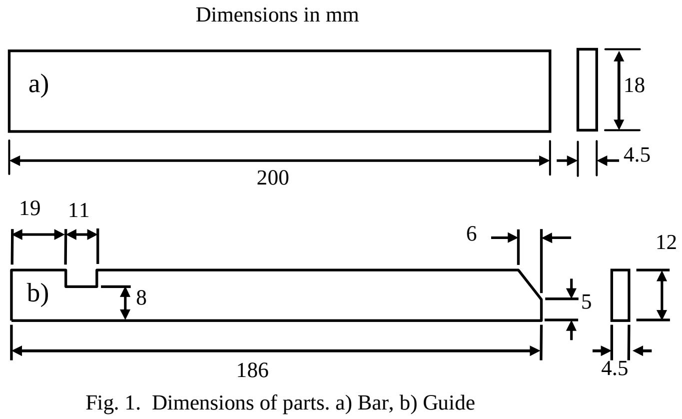

Fig. 1. Dimensions of parts. a) Bar, b) Guide

II. Crack Compliance Method [12]

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.

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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 n^{th} order polynomial series as:

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

where A_i are the coefficients that have to be obtained and P_i are a power series, x^0, x^1, x^2, …. 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. The change in the strain energy due to the presence of the crack and a virtual force is given by *Cheng, Prime and Finnie* as:

$$U = \frac{1}{E'}\int_0^a (K_I + K_{IF})^2 \, da \quad (2)$$

where K_I is the stress intensity factor due to the known stress field and K_{IF} is the stress intensity factor due to the virtual force *F*. Applying Castigliano´s theorem, the displacement *u(a,s)* can be determined by taking a derivative of the strain energy with respect to the virtual force, as:

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

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

$$\varepsilon(a_j, s) = \frac{1}{E'}\int_0^a K_I(a) \frac{\partial^2 K_{IF}(a,s)}{\partial F\,\partial s} da\bigg|_{F=0} \quad (4)$$

The strain $\varepsilon(a,s)$ (where *a* = crack length and *s* is the distance between the location of the strain gauge and the crack plane) due to the stress fields $P_i(x)$ is known as the compliance function $C_i(a_j,s)$ and is given by:

$$C_i(a_j, s) = \frac{1}{E'}\int_0^{a_j} K_I(a) \frac{\partial^2 K_{IF}(a,s)}{\partial F\,\partial s} da \quad (5)$$

Due to the linearty of K_{IF} with *F*, the second term under the integral in (5) is the same as *Z(a)* in:

$$Z(a) = \frac{B}{F}\left(\frac{\partial K_{IF}}{\partial s}\bigg|_{s=0} \right) \quad (6)$$

with *B = 1*, therefore it can be written:

$$C_i(a_j, s) = \frac{1}{E'}\int_0^{a_j} K_I(a) Z(a) da \quad (7)$$

$K_I(a)$ is the stress intensity factor due to the residual stress field, when the crack depth in the beam is equal to *a*. $K_{IF}(a)$ is the stress intensity factor corresponding to the same depth due to a pair of virtual forces *F* applied tangentially at a position on the beam where strain measurements will be taken during the *CCM* cutting of the slot (where *Z(a)* is a geometry dependant function (3)):

$$Z(a) = \frac{\partial^2 K_{IF}(a,s)}{\partial F \partial s} \quad (8)$$

By following the weight function approach, $K_I(a)$ and $K_{IF}(a)$ can be expressed as [10]:

$$K_I(a) = \int_0^a h(x,a)\sigma_y(x)dx \quad (9)$$

$$Z(a) = 4.283\int_0^a h(x,a)(1-2x)dx \quad (10)$$

where $\sigma_y(x) = P_i(x)$ and *h(x,a)* is known as the weight function. So, the $\sigma_{yF}(x)$ is the stress field due to the virtual force *F*. Once the $C_i(a,s)$ solutions are determined, the expected strain due to the stress components in (1) can be obtained as:

$$\varepsilon(a_j, s) = \sum_{i=0}^{n} A_i C_i(a_j, s) \quad (11)$$

The unknown terms A_i are determined so that the strains given by (11) match those strains measured in the experiment during cutting, this is $\varepsilon(a_j,s)_{actual}$. In order to minimize the average error over all data points for an n^{th} order approximation, the method of least squares is used to obtain the values of A_i. Therefore the number of cutting increments *m* is chosen to be greater than the order of the polynomial, i.e. $m > n$. This work used $n = 7$ with 8 constants A_i and $m = 9$, this being the number of experimental slot cutting depths at which strain readings were collected. The least square solution is obtained by minimizing the square of the error relative to the unknown constant A_i [12]:

$$\frac{\partial}{\partial A_i}\sum_{j=l}^{m}\left[\varepsilon(a,s)_{actual} - \sum_{k=0}^{n} A_k C_k(a_j, s) \right]^2 = 0 \;\; i = 0, \ldots\ldots n \quad (12)$$

This gives $[H]\{A\}=\{J\}$ where $[H]=[C]^T[C]$ and $\{J\}=[C]^T\{\varepsilon_j\}_{actual}$ [13] gives a linear set of simultaneous solutions from which A_i values are determined and (1) is then used to determine the residual stress distribution. The numerical procedure was implemented in a FORTRAN program.

II. Procedure

The residual stress field, which is generated by a die process during the manufacture of a guide for an assault rifle (Figure 2), is evaluated. The material is an AISI 1018 steel, which has tensile strength of 485 MPa and yield stress of 310 MPa.

Fig. 2. Manufacturing of the guide

For a complete understanding of the resultant residual stress field, measurements were performed in two directions:

1. Measurement of residual stress field along the axial direction (Figure 3a)
2. Measurement of residual stress field perpendicular to the axial direction (Figure 3b).

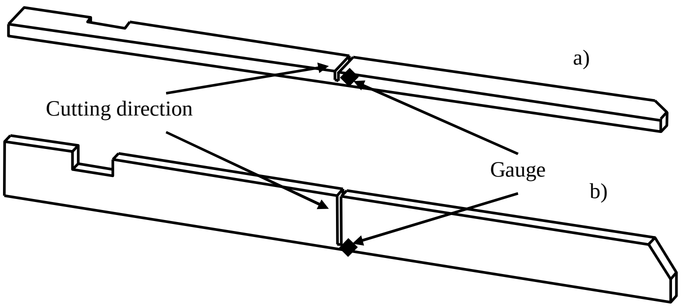


Fig. 3. Cutting direction for measuring residual stress field.
a) Horizontal cut, b) Vertical cut

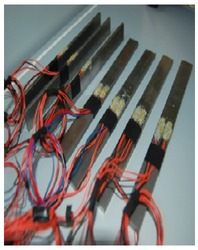
The AISI 1018 steel bars were annealed to remove any previous loading history before the die process was performed. The annealing process was carried out, in a controlled atmosphere furnace at a temperature of 840 º c during 840 min. Thereafter, the specimens were left in the furnace to slowly cool down. To verify that the annealing process was performed correctly, a beam specimen was instrumented with strain gauges and the CCM was performed to determine the residual stress field acting in the material. Subsequently, a batch of beam specimens was subjected to the die process to manufacture the guide and the residual stress field was evaluated. The specimens were the instrumented with strain gauges as shown in Figure 4.

III. Characterization by CCM

The CCM is a destructive method that introduces an increasing slot to determine the stress state into a component. The length of the slot is controlled by small cuts. The introduction of the slot produces a partial relaxation of the acting residual stress field at the neighborhood of the cut. By measuring the strain relaxation, it is possible to determine the actual residual stress profile.

In this research, the cut was performed by an electro-erosion machine (mark SODIK, model AG55L). It was used in order to avoid the induction of additional residual stresses by cold work into the material.

a)



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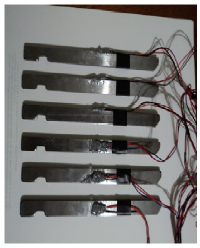
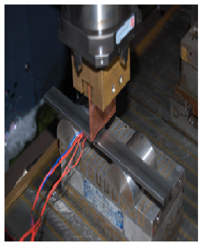


Fig. 4. Strain gage instrumentation. a) Bar. b) Guide.

a)



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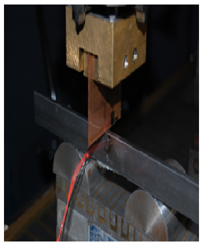

Fig. 5. CCM in the beam bar. a) Horizontal cut, b) Vertical cut

In Figures 5 and 6 are presented the way in which the cuts were produced in each one of the specimens. A copper plate (50 mm X 50 mm X 0.56 mm) was used as cutting tool for the electro discharge process. The electro-erosion machine cut an excess of 0.2 mm per cycle, so it was decided to perform controlled cuts approximately 1 mm deep and strain readings were obtained. Due to the bars dimensions, the number and magnitude of the cuts are given as follows; for the beam bar and guide produced by a die process in a horizontal position (Figure 5a and 6a), 17 and 11 successive cuts were performed respectively, each one being 1 mm deep. For the beam bar and guide produced by the die process in a vertical position (Figure 5b and 6b) 10 cuts were performed. Each one was 0.4 mm deep.

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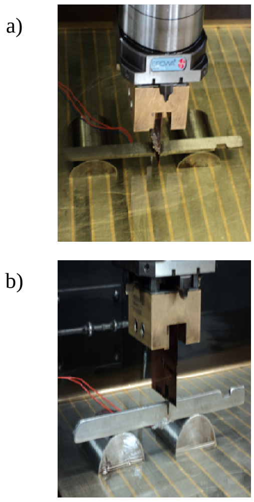

Fig. 6. CCM in the guide. a) Horizontal cut. b) Vertical cut.

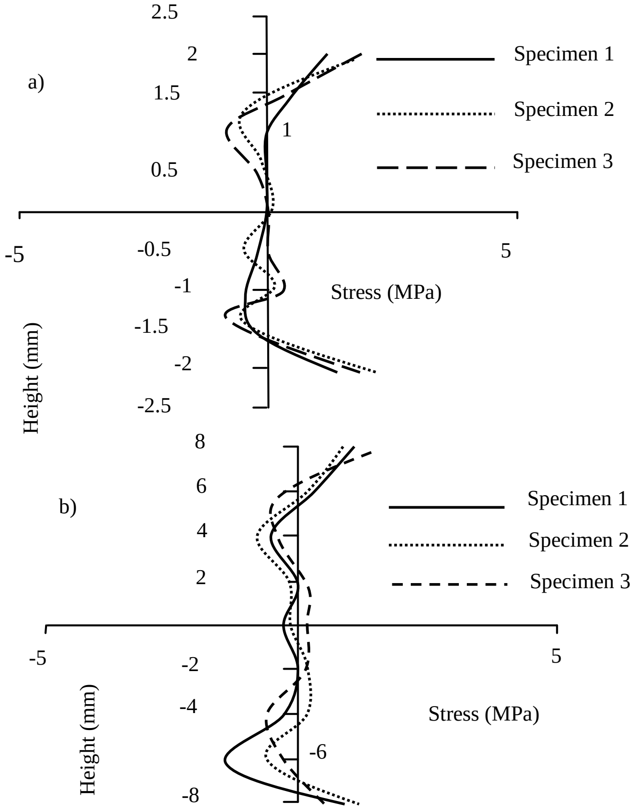

Fig. 7. Residual stress field in annealing beam bar.
a) Horizontal cut. b) Vertical cut.

IV. Results

In Figures 7 and 8 are shown the results obtained by the implementation of the CCM. It can be seen from Figures 7a and 7b, the residual stress field in the beam bars subjected to annealing process. It is possible to see that the elimination of the prior loading history was successful. Almost a non existing residual stress field was achieved, as the reading for both figures is a consequence of the cutting process or alteration caught by the strain gauge.

In Figures 8a and 8b are shown the residual stress field caused by the manufacturing process to create the component. It is possible to observe that the residual stress field found in the annealed beam bars (Figures 7a and 7b) are almost negligible in comparison with the specimens treated by the die process. This confirms that the residual stresses induced by previous loading history, have been removed.

Figure 8 shows the residual stress fields obtained in two directions. Although the magnitude of the residual stress field is not critical, it can be harmful, due to presence of tension residual stresses on the surface of the specimen. This is the place in which fatigue failures develop. This situation has to be considered in the design phase.

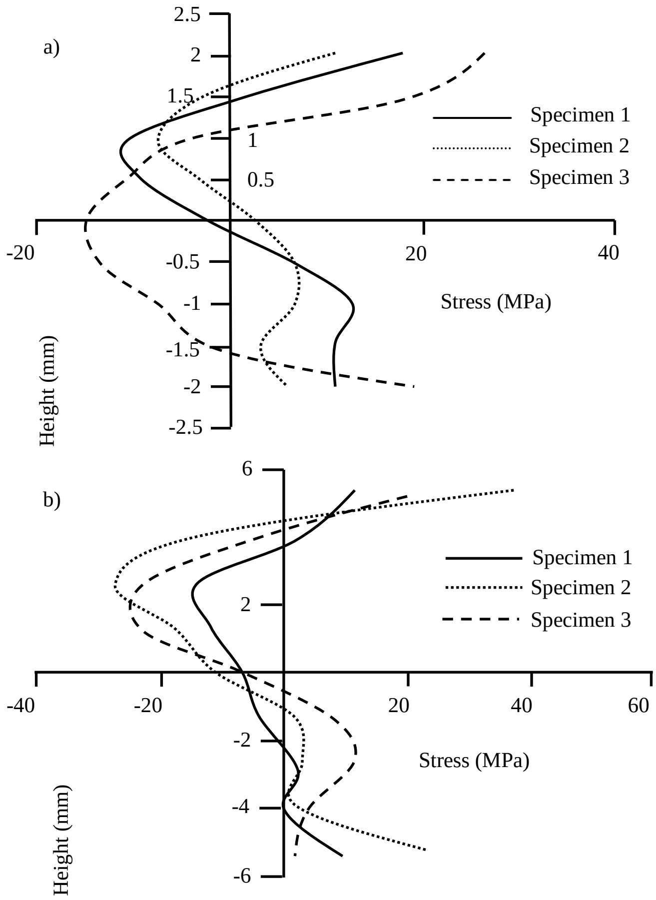

Fig. 8. Residual stress field due of die process.
a) Horizontal cut, b) Vertical cut

V. Conclusion

The knowledge of the effects caused by manufacturing processes on the mechanical behavior of components is of utmost importance; this knowledge can promote the eradication of sudden failures or in-habilitate possible existing cracks to propagate. This research was focused on the measurement of residual stress fields generated by the die process. It should be taken into consideration that the final component has a detrimental residual stress field, which can promote the nucleation and propagation of cracks. This is because a tensile residual stress is active at the surfaces of the component, which will be an adding effect to the action of any kind of external agent. This detrimental effect is an entire consequence of the dying process, which has to be sooner or later modified or change to enhance a much longer service life into the component.

It could be interesting to develop a numerical analysis, to promote an easy manner to apply the CCM. Also, the numerical simulation could provide data to improve the

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assembly of the specimen on the testing rig. As there are residual stresses, deformations have been induced. Therefore, it is important to evaluate the way in which the specimen is hold. This will lead to more accurate readings.

Furthermore, the numerical investigation is a powerful tool that could provide the expected results for a particular case, which later could be corroborated by the experimental procedure and have proved that the introduction of a residual stress field could raise or decrease the mechanical resistance of the material.

Additionally, it could be said, that a mechanical procedure (like the introduction of a residual stress field) may extend the working life of a component if its performance is known and the type of consequences that could bring.

On the other hand, it has been determined that the use of CCM is a very easy method, to obtain full knowledge of the internal state of the material, besides being a quick and easy technique.

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