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Experimental application of the crack compliance method in beams with hardened surfaces

G. Urriolagoitia-Sosa, J.M. Sandoval-Pineda, E.A. Merchán-Cruz, and R.G. Rodríguez-Cañizo
Instituto Politécnico Nacional, Sección de Estudios de Posgrado e Investigación,
Escuela Superior de Ingeniería Mecánica y Eléctrica, Unidad Azcapotzalco,
Av. de las Granjas 682, Col. Santa Catarina, Azcapotzalco, México, D.F. 02550, México.

G. Urriolagoitia-Calderón, L.H. Hernández-Gómez, R. Rodríguez-Martínez, and R. Torres-Martínez
Instituto Politécnico Nacional, Sección de Estudios de Posgrado e Investigación,
Escuela Superior de Ingeniería Mecánica y Eléctrica, Unidad Zacatenco,
Edif. 5, 2 Piso, Lindavista, México, D.F. 07738, México,
e-mail: guiurri@hotmail.com

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In general the mechanical design is developed by considering the lineal behavior of the components, which means that the stress reached by the requested work that takes place is under the yield stress. The stresses left in the component are known as residual stresses. This kind of stress has the characteristic of been either beneficial or damaging depending on their direction. They exist without the application of external agents and are able to extend or reduce the components lifetime, hence the importance of their study and evaluation. This paper presents the obtained results on the residual stress field evaluation induced in a beam. Three cases involving superficial hardening are analyzed, namely; hardened surface by laser shot, hardened surface by shot-penning, and superficial hardened by four points bending and pre-pulling. In this research the *Crack Compliance Method* was applied to evaluate the residual stress field induced in each case. This method consists in the introduction of a slot of incremental depth. The cut relaxed the residual stress field, and then the relaxed strain can be measured by strain gauges to quantify the original stress state.

Keywords: Residual stress; crack compliance method; shot peening; bending; laser peening.

En general el diseño mecánico se desarrolla mediante consideraciones de trabajo lineal en el componente, lo que significa que el estado de esfuerzos alcanzados por el trabajo aplicado se encuentra por debajo del esfuerzo de cedencia. En realidad, en algunas ocasiones el nivel de esfuerzo alcanzado rebasa el esfuerzo de cedencia. Los esfuerzos que quedan en el componente se conocen como esfuerzos residuales, los cuales tienen la característica de ser benéficos o detrimentales dependiendo de su dirección. Existen sin la aplicación de un agente externo y pueden prolongar o reducir el tiempo de vida de un componente, por lo que es importante su estudio y evaluación. En este artículo se presentan los resultados obtenidos en la evaluación de campos de esfuerzos residuales inducidos en vigas. Tres casos con endurecimiento superficial son analizados, los cuales son; endurecimiento superficial por laser, endurecimiento superficial por granallado y prejalado de vigas en flexión. En esta investigación se aplica el Método de Respuesta de Grieta (CCM) para evaluar el campo de esfuerzos residuales inducido en cada caso. Este método consiste en introducir un corte de profundidad creciente. El corte relajará el campo de esfuerzos residuales, y las deformaciones relajadas pueden ser medidas por galgas extensométricas para cuantificar el estado original de esfuerzos.

Descriptores: Esfuerzos residuales; método de respuesta de grieta; granallado; flexión; láser.

PACS: 07.05.Fb; 07.05.Hd; 42.62.Cf; 62.20.Fe

1. Introduction

Around the world it is well known that superficial hardening in mechanical components induces anisotropic behavior on the material [1-2]. In addition, if the hardening of the material is performed in a non homogenous manner, one of the consequences is the introduction of a residual stress field. The knowledge of the effect of residual stresses on mechanically loaded materials can be helpful to select materials for engineering applications and in determining suitable loading in the mechanical design [3]. A number of authors have evaluated residual stresses in materials, they have used numerous and diverse techniques [4-6]. The methods for their evaluation are classified in three groups, which are; nondestructive, semi-destructive and destructive [7]. After reviewing a great deal of research information and taking into consideration all the aspects in the experimental methods for the evaluation of residual stresses, it was taken the decision to develop and use the Crack Compliance Method (*CCM*) [8-10]. The *CCM* is a relatively inexpensive method for determining residual stresses in materials. Only the elastic constants of the material and data on strain relaxation, when a slot is introduced into the material, are required for the application of the method. Compared to other techniques, such as X-Ray and neutron diffraction methods (non destructive methods, in some cases, tend to misread defects in the material like dislocations, vacancies and residual stresses), the *CCM* is relatively simple and requires more commonly available equipment such as an electric discharge machine (*EDM*) and strain gauges. The *CCM* is however a destructive method as it requires cutting a slot in the piece or material of interest. It is also sensitive to errors in measurement of strains especially when gauges are placed close to the slot.

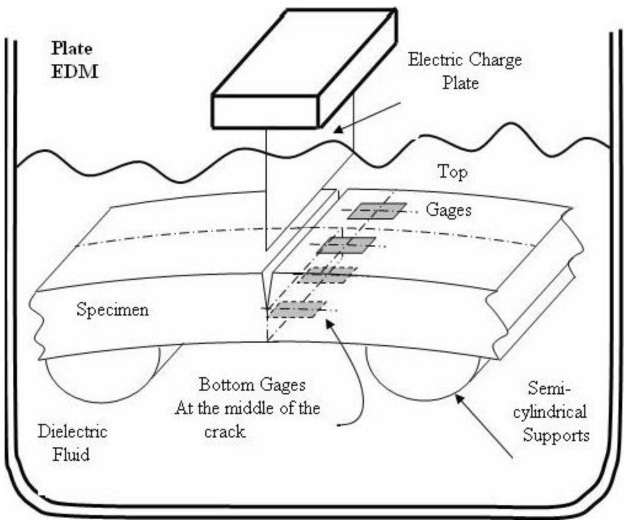

FIGURE 1. *CCM* procedure representation.

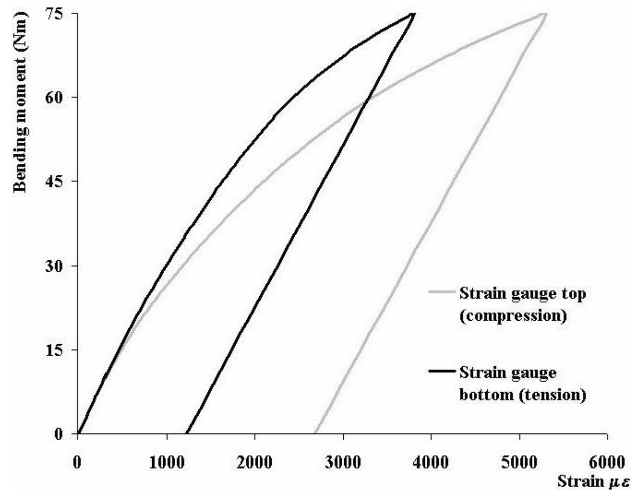

FIGURE 2. Bend test in AISI 1045 steel pre-pulled to 25000 microstrain.

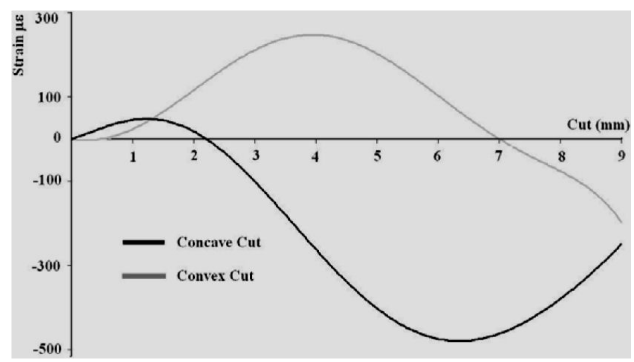

FIGURE 3. Strain results by cutting for AISI 1045 steel pre-pulled to 25000 microstrain.

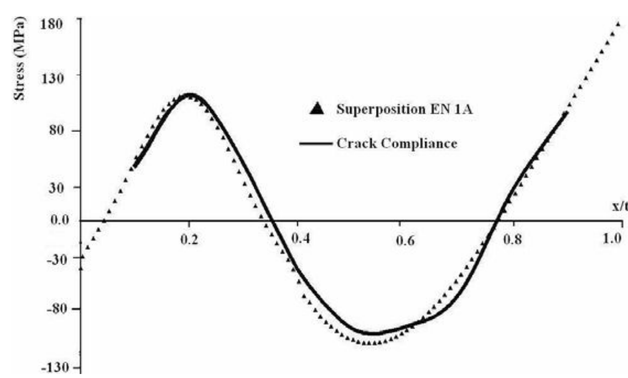

FIGURE 4. Residual stress evaluation in AISI 1045 steel pre-pulled to 25000 microstrain.

2. Experimental procedure

In this paper are presented three cases were the *CCM* was used Fig. 1 [3,4,8,10,13,14]. The first case analyzed is the evaluation of a residual stress field induced on a pre-pulled bended beam. For the second cases a beam shot peened was analyzed and the residual stress field was quantified. Finally, a beam having a residual stress field introduced by laser shot peening was studied and assessed. In some cases, it was possible to confirm the residual stress field induced in the specimen by an analytic and/or numerical method, where this was possible the results are presented and a comparison can be performed. The comparison (where it was possible) can assess the precision in the results obtained from the *CCM*. The cases of study are as follow.

3. Results and discussion

3.1. Pre-pulled bended beam

A batch of AISI 1045 steel specimens with 10 by 10 mm section bars was stress relief annealed and was used to test for the effect of pre-straining. A mechanical loading operation was performed on the batch in order to induce previous history effect after the stress relief annealing process was completed. A group of specimens were axially pulled to 25000 $\mu\varepsilon$ to produce a severe level of strain hardening and later they were bended to induce a residual stress field. Figure 2 shows the average bending moment against strain plots for the pre-pulled group (behaviors were plotted in the same quadrant). An earlier yielding can be observed on the compressive surface of the beams. The unsymmetrical yielding on the two sides of the beams will lead to an unsymmetrical residual stress field in the specimens. The strain results obtained from the cutting procedure can be seen in Fig. 3. From Fig. 3 it can be seen that whatever the setting of the shape of the specimen at the moment of the cut, a non-symmetrical response of the strain data was obtained. This unsymmetrical strain response was because the surface under tensile effect has an elevated yield stress (in comparison to the original yield stress) due to the strain hardening process and the surface under compression has a lower yield stress (in comparison to the original yield stress) due to Bauschinger effect. This was expected, because the residual stress profile was not symmetrical. Figure 4 shows very good agreement between the results obtained using the Crack Compliance Method and those obtained from superposition of the loading and unloading stresses.

3.2. Shot peened beam

A second group of specimens (AISI 1045 steel) with a base of 38.1 mm by 12.7 mm high cross-section bars was stress relief annealed and was used for the evaluation of residual stresses introduced by shot peening. By considering the hardness of the selected material for the tests, shot peening balls were selected and bought. The shot peening ball selected was S-230 with a 0.6 mm diameter [11]. The shot peening process was performed with a pneumatic machine and as indicated by the *ASM handbook* [12]. The shot pressure used by the machine was of 5 bars. After the shot peening process was finished, a strain gauge was lay down at the unshot peening surface and used for obtaining the relaxed strains caused by the EDM cut. These strains will be used to determine the residual stress field in the beam. The strain results obtained from the cutting procedure can be seen in Fig. 5. In Fig. 6 it can be seen the results obtain by the *CCM* and a comparison against Finite Element Method (FEM).

3.3. Laser shot peened beam

A third group of aluminum specimens (6063 T5) with 6.35 mm by 15 mm section bars was stress relief annealed and was used for the evaluation of residual stresses introduced by laser shot peening. This process is not the traditional laser shot peening process, because does not used the generation of plasma by heat, the hardness in the material was performed by inducing the laser directly to the material. In this process the laser impact is around of 26 ps (which gives a better intensity of high energy). It is used a Nd-Yag laser, 1064 wave length and 532–355 NM armonics. The irradiation was performed by one shot with a systematic variation of energy from 1 to 20 mJ, by employing a haz diameter of 4 mm. On the other hand, the incitation in each point was of 5 pulses with a frequency of 1Hz. After the laser shot peening process was finished, a strain gauge was lay down at the untreated surface and was used for obtaining the relaxed strains caused by the EDM cut. These strains will be used to determine the residual stress field in the beam. The strain results obtained from the cutting procedure can be seen in Fig. 7. In Fig. 8 it can be seen the results obtained by the *CCM*. In this particular case it was not possible to perform an analytical or numerical comparison. The importance of using data from a strain gauge location for *CCM* analysis to obtain a unique residual stress distribution in a beam was demonstrated by several cases of study in this paper. Only one strain gauge was needed in each case for the evaluation of the induction of different residual stress fields induced. It was found and confirmed that a single gauge placed opposite to the slot

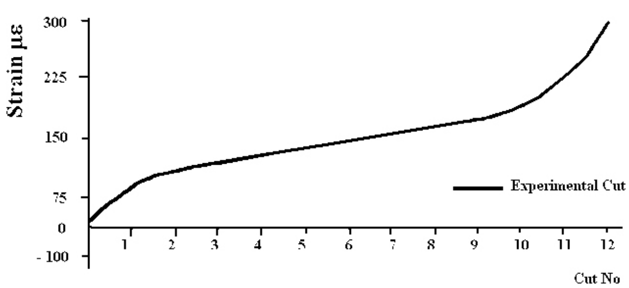

FIGURE 5. Strain results by cutting for AISI 1045 steel shot peened by S-230 ball.

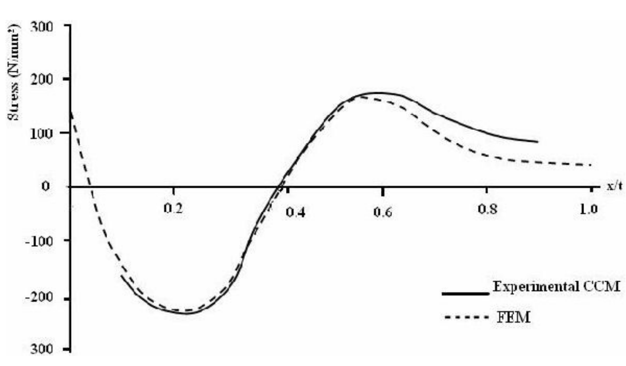

FIGURE 6. Residual stress evaluation in AISI 1045 steel shot peening by S-230 steel.

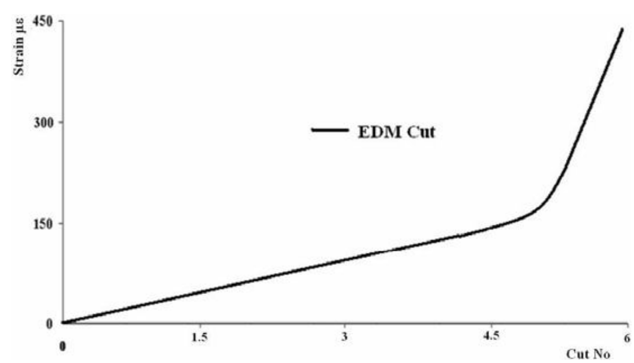

FIGURE 7. Strain results by cutting for 6063 T5 laser shot peened.

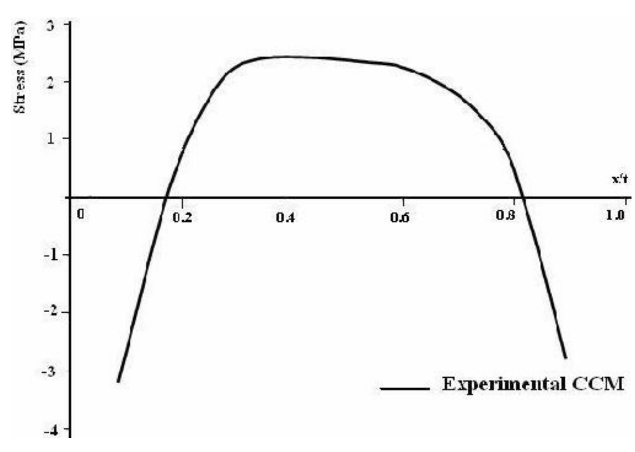

FIGURE 8. Residual stress evaluation in 6063 T5 Aluminum laser.

gave good residual stress results for up to 85% of the depth of the beams in most cases. All the specimens employed in this research were stress relief annealed [4] to eliminate previous history and only had the residual stress field from plastic loading.

4. Discussions

The first case of study (bending of a pre-pulled beam) was performed to validate the *CCM* analysis, because the residual stress profile can be corroborated very easily by analytical methods (loading and unloading superposition). The relevance and interest in this case of study was to demonstrate the capability of the *CCM* to reveal the effect of strain hardening on residual stresses in beams that had been strain hardened and then bent plastically. The unsymmetrical yielding on the two sides of the beams during bending led to dissimilar residual stress field magnitudes on the tensile and compressive sides. Compared to annealed materials, the residual stresses developed in the beams with prior straining show asymmetry in magnitude of the stresses on the tensile and compressive sides. The second case (shot peened beam) it was important to show the accuracy of the *CCM* under residual stress conditions of low magnitude and introduced by damaging one of the surfaces of the specimen. A finite element analysis was performed in this study to validate the *CCM* and to evaluate their capacity and limits, so it can be fully used for the next case. The shot peening process is extremely used in the automotive industry, but there are not accurately known their consequences and benefits. The third case (laser shot peened beam) was performed after the assessment on the level of accuracy on the *CCM* was fined. The results obtained have shown a very well defined profile, where the compressive residual stress are present at the laser processed surface, which is where they are supposed to be. It can also be seen in Fig. 8, that the residual stress field showed some kind of similitude between the areas below the line of tension and compression, as how it was supposed to be and this kind of residual stress profile could be advantageous for the retardation of crack propagation.

5. Conclusions

In general the results obtained from the *CCM* closely agree with those obtained by using other methods and the result obtained for the last case of study are very encouraging. A support system which allows free movement of beams during relaxation of residual stresses while cutting of slots has also been presented. The method allows the plane of crack slots to be maintained as cutting progresses. The authors have confidence in the results obtained by the *CCM*, because of the variety in the cases of study, the manner it has been performed and the results fined.

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