

Using fracture mechanics for determining residual stress fields in diverse geometries

Aplicación de la mecánica de la fractura para determinar esfuerzos residuales en diversas geometrías

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ABSTRACT

Component deterioration due to a crack is of the highest importance for the engineering community. Fracture mechanics have mainly been used for studying and evaluating crack or defect nucleation and propagation. This article presents a methodology based on inducing a crack (cut) into mechanical components to characterise an induced residual stress field. This research work's originality was aimed at highlighting fracture mechanics' role in detecting possible component destruction by energetic analysis of crack propagation and evaluating service-life to be used as a technique for characterising the effect of prior loading history regarding a given material. The technique presented in this work is known worldwide as the crack compliance method, based on linear elastic fracture mechanics principles developed by Vaidyanathan and Finnie. Three studies are shown (bent beam, pressurised pipe and modified SEN specimen) where components were induced with a residual stress field. The way non-homogeneous loading could introduce a residual stress field is also presented; if residual stress field acting on a specimen has been characterised, then the mechanical process can be manipulated and a beneficial effect induced into the material.

Keywords: Crack compliance method, residual stress, non-homogeneous loading.

RESUMEN

El deterioro de los componentes debido a falla es un fenómeno que ha recibido constante atención por la comunidad ingenieril. Por su parte, el estudio de la nucleación y propagación de grietas o defectos se analizan principalmente según los principios científicos de la mecánica de la fractura. En este artículo se presenta un método de evaluación desarrollado a partir de la inducción de una grieta (corte) en componentes mecánicos para determinar o caracterizar el campo de esfuerzos residuales actuante. La originalidad de este trabajo resalta en la aplicación de la mecánica de la fractura, que es una ciencia dirigida a detectar la posibilidad de destrucción de un componente mediante el análisis energético de propagación de grietas y evaluación de su vida útil, lo que es utilizado como una técnica para caracterizar el efecto ocasionado por la historia de carga previa en un material. La técnica que aquí se presenta es conocida internacionalmente como método de respuesta de grieta (crack compliance method). Dicho método está fundamentado en principios de mecánica de fractura lineal elástica y fue inicialmente desarrollado por Vaidyanathan y Finnie. En este artículo se presentan tres casos de estudio —viga flexionada, tubo presurizado y probeta SEN modificada— en los cuales los especímenes fueron inducidos con campos de esfuerzos residuales. Asimismo, se presenta la manera como la aplicación de cargas no homogéneas introduce un campo de esfuerzos residuales, al conocer la magnitud y características de este campo es posible manipular el proceso mecánico para producir un efecto benéfico en el material.

Palabras clave: Método de respuesta de grieta, esfuerzos residuales, cargas no homogéneas.

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Introduction

For several decades now the scientific community has devoted itself to the task of determining the reasons and way in which components fail; fracture mechanics arose from such need and facilitates analysing component failure in mechanical structures. Failure analysis is aimed at determining how and why mechanical components do not fulfil expected service life when cracking occurs. It has been determined that causes promoting material failure are fatigue, structural overload, wear, corrosion and micro-faults (Urriolagoitia-Calderon *et al.*, 1997; Hernández-Gómez *et al.*, 2009; Gilbert *et al.*, 1994; Lu, James and Roy, 1996). Other variables to be considered would be the type of component application and human factors (O'Connor *et al.*, 2002; Kohn *et al.*, 2010; National Research Council, 1998) such as wrong application and abuse, assembly mistakes, manufacturing faults, inappropriate maintenance, design mistakes, faulty material selection, environmental damage and inadequate thermal treatment. The main objective of failure analysis is to understand the root of the problem regarding cracked components, thereby enabling the prevention of similar cases in the future. Nevertheless, by now, and based on scientific advances, this article presents the possibility of using fracture mechanics knowledge to determine a material's physical characteristics and the mechanical effects produced by previous loading on components by inducing a crack or cut. Fracture mechanics enables determining the condition of a residual stress field produced by the action of external agents and applying such characterisation facilitates manipulating manufacturing processes to improve a particular material's mechanical properties (Cheng and Finnie, 1990a).

Inducing residual stress in a material is an intrinsic operation caused by fabricating mechanical components, as most manufacturing processes introduce residual stress into a component. Residual stresses are effects remaining active in a material without the action of a load and are the consequence of applying an external non-homogeneous agent exceeding a material's yielding point. Residual stresses are self-equilibrating (tension and compression coexist) and greatly influence a material's mechanical behaviour (Withers and Bhadeshia, 2001; Brinksmeier *et al.*, 1982; Fu *et al.*, 2009). The scientific literature has widely identified such stresses' importance in failure development. Likewise, residual stresses very often cause dimensional instability, once dimensional distortion has been applied after being heat-treated or after machining. The importance of residual stresses is based on the fact that they are produced by all fabrication processes and that they exist in a component regardless of external agent action, thereby being very difficult to determine (Beghini and Bertini, 1990; Ritchie and Leggett, 1987; Galatolo and Laciotti, 1997; Orkisz and Skrzat, 1996).

Methods for evaluating induced residual stress fields can be divided into three groups; destructive, semi-destructive and non-destructive. The crack compliance method (CCM) is a destructive method; it has been known by different names such as successive extension of crack technology, successive cracking method, hollowing method, RUT rectilinear method. Cheng and Finnie coined the crack compliance method (CCM) name (Cheng and Finnie, 1988, 1990b and 1994). CCM initiates Schwaighofer's work (1964) which deserves mention as being the first to use a groove to measure residual stress. In fact, two grooves were manufactured into a component and residual stress field determined using strain gauges. The CCM as we know it was developed by Vaidyanathan and Finnie (1971); they measured the residual stress field acting on a plate welded end, by introducing a hole and then extending the groove from the hole using a

jeweller's saw. Then, for every increase in groove length, stress intensity factor K_I was determined by applying photo-elastic technology. Inverse technology was applied to find a solution near the residual stress field acting on the component. Technological advances by the mid-1980s stimulated investigation to use the CCM. This research trend continued in later years (Prime, 1999) in:

- the USA (Cheng and Finnie, 1988, 1990a, 1990b and 1994, Prime, 1999 and 2000);
- Holland (Ritchie and Leggett, 1987);
- the UK (Ritchie and Leggett 1987; Nowell, Tochilin and Hills, 2000; Reid, 1988; Urriolagoitia-Sosa, Durodola and Fellows 2007);
- Germany (Fett and Thun, 1996);
- South Korea (Kang, Song and Earmme, 1989);
- Mexico (Urriolagoitia-Sosa, 2005; Urriolagoitia-Sosa *et al.*, 2007 and 2009);
- Switzerland (Schindler and Landolt, 1997; Schindler and Bertsschinger, 1997);
- Italy (Galatolo and Laciotti, 1997);
- Poland (Orkisz and Skrzat, 1996); and
- China (Oh, Lai and Nee, 1993; Lai and Siew, 1995).

Most CCM applications have involved using common metals (high, medium and low carbon steel, stainless steel, bio-compatible metals, aluminium alloy, etc) (Prime, 2000; Jones and Dunn, 2008; Nervi *et al.*, 2009). Research by Fett and Thun (1996) involved using PMMA and PVC whereas Herman (1995) successfully applied CCM in materials having a metal matrix.

This paper analyses how inducing a cut (crack) into a mechanical component can be used to characterise the residual stress field acting on a component. Three experimental study cases are analysed: a bending beam (without and with previous loading history), a pipeline subjected to service pressurised conditions and a modified SEN specimen used for crack arrest analysis. Inducing a residual stress field in each specimen altered the materials' mechanical resistance and consequently modified a component's mechanical characteristics. It also describes the manner in which non-homogeneous loads are applied to introduce a specific residual stress field for every case and how a mechanical process might be manipulated to produce a beneficial effect in a particular material (Peyre *et al.*, 2000; Kudryavtsev, 2008; John, Jata and Sadananda, 2003). A residual stress field's beneficial aspect can only be induced if external agent application magnitude and form is known and the field characterised, so that the effect of an external agent can be modified or some other external agent added to generate an expected beneficial effect.

The crack compliance method's theoretical basis (Urriolagoitia-Sosa, 2005)

This methodology was developed by Vaidyanathan and Finnie in 1971 and afforded the possibility of an acting residual stress field being obtained in a mechanical component by means of the stress intensity factor when a crack was introduced into a given material (Prime, 1999). A crack can be induced by producing an initial cut, making it extend slowly in a controlled way; nevertheless, cases have been detected where a cut induced cold has altered the original residual stress field acting on a component. It was thus proposed to make a cut by means of electro-erosion technology and thus eliminate this problem. When a cut is made in a material presenting a residual stress field, there is partial relaxation of such residual stress field due to stress rearrange-

ment in the body causing deformation (Figure 1). Deformation by inducing a cut can be determined by using strain gauges. Such cut would eventually transform a residual stress field originally acting on material, so deformation produced by relaxation effects is used by the CCM to determine the residual stress field in a given material. A residual stress field from deformation or strain produced by relaxation can be determined in two ways: direct solution and/or inverse solution method (Prime, 1999). Both techniques are based on linear elastic fracture mechanics principles. An inverse solution is described.

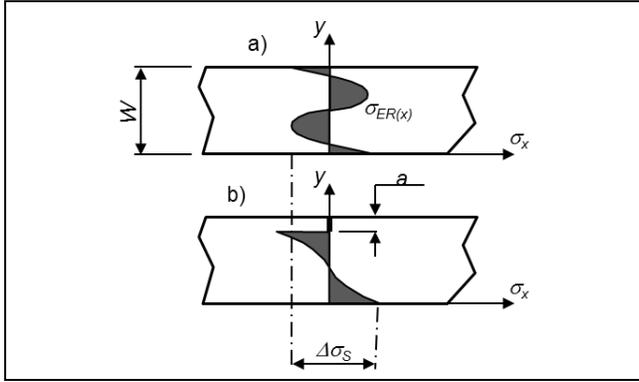


Figure 1. Bidimensional arbitrary body. a) Residual stress initial state, b) Rearranging the residual stress field caused by inducing a crack (cut)

Consider a bi-dimensional arbitrary body suffering the effect of longitudinal cracking “a” and a residual stress field (Figure 2). When the crack length is extended by a small increase δa , a strain change at the surface of the body $\delta \epsilon_M$, takes place. This can be expressed by Castigliano’s theorem (Todd, 1981) as:

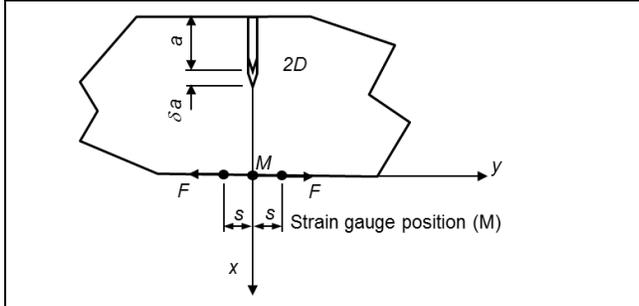


Figure 2. Stress intensity factor and strain relationship for arbitrary point M

$$\delta \epsilon_M = \frac{1}{2} \frac{\partial^2 \delta U}{\partial F \partial s} \Big|_{F=0} \Big|_{s=0} \quad (1)$$

where δU is elastic energy in a component stored before and after crack extension, F is an acting virtual force and s is the distance from arbitrary point M . The elastic energy difference, in terms of stress intensity factor, present before and after crack extension is expressed by (Irwin, 1957):

$$\delta U = \frac{B}{E'} \left\{ [K_{Irs} + K_{IF}]^2 + [K_{IIrs} + K_{IIF}]^2 \right\} \delta a \quad (2)$$

E' is the generalized Young’s modulus ($E' = E$ for plane stress condition and $E' = E/(1-\nu^2)$ for plane strain condition), B is the thickness of the body. At the crack tip K_{Irs} and K_{IIrs} are stress intensity factors caused by residual stress field, K_{IF} and K_{IIF} are the stress intensity factors due to applying a virtual force. Substituting Equation 2 in Equation 1 and as K_{IF} is a linear function de-

pending on F and K_{Irs} is independent of s (Schindler and Landolt, 1997), would give:

$$\delta \epsilon_M = \frac{B}{E' F} \left[K_{Irs} \frac{\partial K_{IF}}{\partial s} \Big|_{s=0} + K_{IIrs} \frac{\partial K_{IIF}}{\partial s} \Big|_{s=0} \right] \delta a \quad (3)$$

This work considered that they did not exist for system K_{IIF} and K_{IIrs} (because it was a symmetrical system regarding the crack plane, and the forces did not lead to shear stress in plane $y = 0$) (Schindler and Bertschinger, 1997), so:

$$\delta \epsilon_M = \frac{B}{E' F} K_{Irs} \frac{\partial K_{IF}}{\partial s} \Big|_{s=0} \delta a \quad (3a)$$

The ratio between strain change at M and stress intensity factor for each crack increase could be obtained by applying Equation 3a, expressed as (Schindler and Bertschinger, 1997):

$$K_{Irs}(a) = \frac{E'}{Z(a)} \frac{d \epsilon_M}{da} \quad (3b)$$

where $Z(a)$ is a function depending on component geometry. The overall inverse polynomial method can be developed from here for determining the residual stress field acting on a component (Urriolagoitia-Sosa, 2005). Consider crack a with length t and unitary body thickness (Figure 3) (Irwin, 1957).

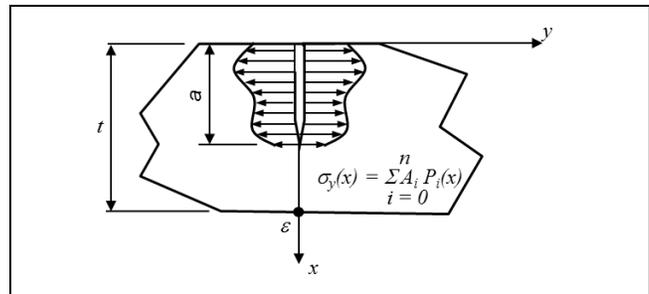


Figure 3. Strain reading at the rear surface produced by a cut (Cheng and Finnie, 1994)

Stress function $\sigma_y(x)$ is unknown, so it has to be determined by using strain measurements ϵ , at the point where a crack will pass ($x = 0, y = s$ or $x = t, y = 0$) (Figure 3). The unknown residual stress distribution in the beam can be represented by adding an n^{th} order polynomial series as (Cheng and Finnie, 1994):

$$\sigma_y(x) = \sum_{i=0}^n A_i P_i(x) \quad (4)$$

where A_i is the coefficient to be obtained and P_i a power series, $x^0, x^1, x^2, \dots, x^n$ etc. Legendre polynomials are also used. However, the CCM includes a step which assumes that stress distribution, $\sigma_y(x) = P_i(x)$, interacting with the crack is known. This known stress field is used to obtain crack compliance function C by using Castigliano’s approach. The change in strain energy due to the presence of the crack and the virtual force must thus be evaluated. Strain energy density represents one alternative; 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. The expression for the intensity of the strain energy density field for an elastic material would be:

$$S = a_{11} K_I^2 + 2a_{12} K_I K_{II} + a_{22} K_{II}^2 + a_{33} K_{III}^2 \quad (4a)$$

This criterion is based on energy field local density at the crack tip and does not require any assumption regarding the direction in which 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 was under mode I. S could thus be combined with Castigliano's theorem. Displacement $u(a,s)$ could be determined by taking a derivative regarding virtual force, as (Cheng and Finnie, 1994):

$$u(a,s) = \frac{1}{2} \frac{\partial u}{\partial F} \Big|_{F=0} = \frac{1}{E'} \int_0^a K_I(a) \frac{\partial K_{IF}(a,s)}{\partial F} da \Big|_{F=0} \quad (5)$$

Differentiating now regarding distance s , strain in x -direction was given by (Cheng and Finnie, 1994):

$$\varepsilon(a_j, s) = \frac{1}{E'} \int_0^a K_I(a) \frac{\partial^2 K_{IF}(a,s)}{\partial F \partial s} da \Big|_{F=0} \quad (6)$$

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

$$C_i(a, s) = \frac{1}{E'} \int_0^a K_I(a) \frac{\partial^2 K_{IF}(a,s)}{\partial F \partial s} da \quad (7)$$

Due to K_{IF} linearity with F , the second term under the integral sign in Equation 7 would be the same as $Z(a)$ in:

$$C_i(a_j, s) = \frac{1}{E'} \int_0^{a_j} K_I(a) Z(a) da \quad (8)$$

By following the procedure developed by Schindler *et al.*, (1994) and Kang *et al.*, (1989) for a beam with strain measurement data at point M , $K_I(a)$ can be expressed as:

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

where $\sigma_y(x) = P_i(x)$ and $h(x, a)$ is known as the weight function. Once $C_i(a, s)$ is determined, the strain due to the stress in a component can be calculated by (Cheng and Finnie, 1994):

$$\varepsilon(a_j, s) = \sum_{i=0}^n A_i C_i(a_j, s) \quad (10)$$

Unknown terms A_i were determined so that the strain given by Equation 10 matched those measured in the experiment during cutting, i.e. $\varepsilon(a_j, s)_{actual}$. To minimise average error over all data points for n^{th} order approximation, the least squares method was used to obtain values for A_i . Therefore the number of cutting increases m was 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 squares solution was obtained by minimising the square of the error relative to unknown constant A_i (Cheng and Finnie, 1994):

$$\frac{\partial}{\partial A_i} \sum_{j=1}^m \left[\varepsilon(a, s)_{actual} - \sum_{k=0}^n A_k C_k(a_j, s) \right]^2 = 0 \quad (11)$$

$$i = 0, \dots, n$$

So:

$$[H]\{A\} = \{J\} \quad (12)$$

This gave $[H]\{A\} = \{J\}$ where $[H] = [C]^T [C]$ and $\{J\} = [C]^T \{\varepsilon\}_{actual}$ (Urriolagoitia-Sosa, 2005, Urriolagoitia-Sosa *et al.*, 2007) giving a linear set of simultaneous solutions from which A_i values were determined and Equation 4 was then used to determine residual stress distribution. A FORTRAN program was used for numerical procedure.

Finite element numerical simulation method

Numerical simulations were developed for each case studied in this work. All numerical analysis was carried out using commercial computational software and the finite element method (FEM), involving structural evaluation, two-dimensional modelling and plane stress theory. An 8-node solid-plane element was used for each numerical study, considering three degrees of freedom (x , and y , rotation in z). Numerical evaluations involved elasto-plastic considerations and a kinematic hardening rule (Urriolagoitia-Sosa, 2005). The model's geometry was developed and the model discretised in a controlled manner, preserving mesh homogeneity (Figure 4). The mechanical properties and external agents in each case study are presented in Table 1. The results are given after the system was unloaded.

Table 1. Mechanical properties and loading conditions

Mechanical properties	Bent beam [48-49]	Pressurised pipe	Modified SEN specimen [45]
Elasticity modulus	190,000 N/mm ²	200,000 N/mm ²	190,000 N/mm ²
Poisson ratio	0.28	0.28	0.28
Yield stress	370 N/mm ²	400 N/mm ²	370 N/mm ²
Yield strain	0.001947	0.002	0.001947
Maximum stress	596.85 N/mm ²	600 N/mm ²	596.85 N/mm ²
Maximum strain	0.024	0.01	0.024
Load	160 N	150 N	100 N
Application of load	Punctual	Punctual	Punctual
Unloading	Lineal	Lineal	Lineal

It should be mentioned that two numerical analyses were performed for the modified SEN specimen, applying the previous considerations. The first study involved an evaluation of the residual stress field considering geometry having a stress concentrator; the effect caused by inducing a 5 mm length cut on introducing a residual stress field was added in the second case (Romero-Ángeles, 2009).

Experimental development

This work involved experimental investigation including three study cases: a bent beam under pure flexion (with and without previous loading history) (Kang *et al.*, 1989; Urriolagoitia-Sosa *et al.*, 2003; Urriolagoitia-Sosa, 2005), a previously pressurised pipe (Cheng and Finnie, 1986) and a modified SEN specimen (Romero-Ángeles, 2009; Urriolagoitia-Sosa *et al.*, 2010a and b). The residual stress field induced in each component was determined for quantifying its effect on the material's mechanical resistance and to propose (if possible) a mechanical process for improving a component's physical characteristics or to define the magnitude of damage resulting from action which could take place in a specimen. For each case of CCM application, a cut was introduced by using an electro-erosion machine with copper plate electrode and considering that supporting the piece was freely relaxed to obtain the strain information.

Bent beam (with and without previous loading history)

Stainless steel alloy AISI 316L was used to induce a residual stress field by pure flexion in a beam (Molina-Ballinas, 2010; Urriolagoitia-Sosa *et al.*, 2010c). The material consisted of transverse rectangular section bars (10 mm height and 6.35 mm base). 12 equal specimens were cut to 250 mm length and were partially annealed at 600°C for 30 minutes in an electric oven and were left inside the oven to slowly cool down (Molina Ballinas, 2010). The intention of annealing the material before introducing the residual stress field was to eliminate any previous loading history preserving the effect of the residual stress field induced in a controlled manner. All beams were instrumented with strain gauges on top and bottom surfaces (Figure 5a). The bottom

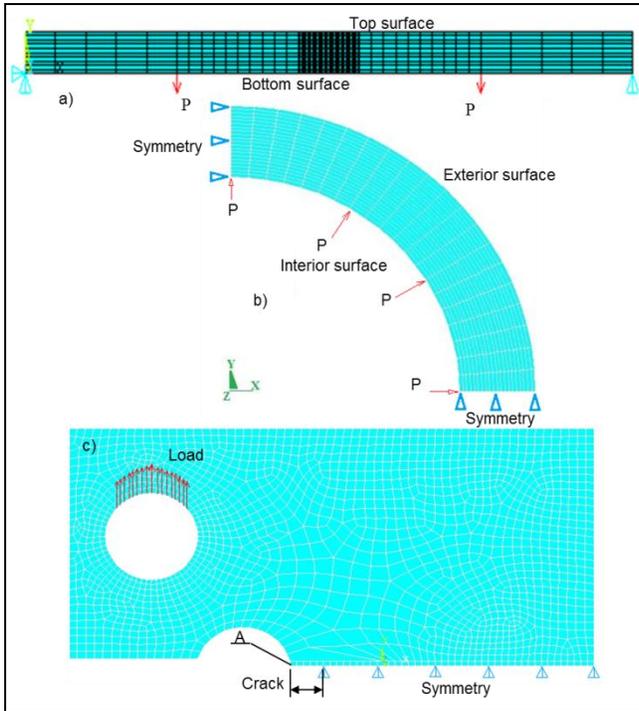


Figure 4. Model discretisation, load application and boundary conditions. a) Four point bending beam, b) Pressurized pipe, c) Modified SEN specimen

strain gauge was then used for CCM. The batch of specimens was separated into two groups of 6 units each. The first group of beams was induced with a residual stress field by pure bending using a servo-hydraulic machine (Figure 5b). The second group of specimens was pre-loaded with homogeneous compressive load before inducing the residual stress field by pure bending. The previous loading history applied by the axial compressive load modified the axisymmetric distribution of the residual stress field induced by the bending procedure; regarding the case lacking previous history, this operation increased the component's mechanical resistance (Urriolagoitia-Sosa *et al.*, 2010c). The second case involved a compressive axial load being applied until the strain gauge reached $13,300 \mu\epsilon$ (beyond yield strain). All specimens from both groups were bent by an INSTRON machine with a 2.5 kN recorded load. This load was big enough to exceed the material's yielding point (for both groups), thus inducing a residual stress field in each specimen.

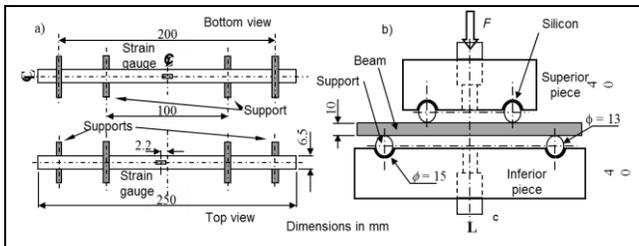


Figure 5. Device for inducing a residual stress field. a) Beam instrumentation, b) Loading system

Once the residual stress field had been induced, the strain gauge on the bottom of the beam was sealed with silicon. The gauge was sealed as protection, since electro-erosion machine cutting needs a specimen to be immersed in a container containing dielectric liquid. A progressive 1 mm length cut was made beginning at the top surface; this cut was aimed at producing rearrangement of the residual stress field and producing a defor-

mation effect. The cut length was verified at the end of each process and the strain value caused by the relaxation was recorded; 9 cuts were made from the top surface of the beam to the bottom surface in every specimen, keeping a 1 mm length of material intact to preserve structural integrity (Molina-Ballinas, 2010; Urriolagoitia-Sosa *et al.*, 2010c). The relaxation produced by 9 cuts was used for determining the original residual stress field using CCM. Figure 6a shows the residual stress field for a beam lacking prior loading history and subjected to pure bending. Figure 6b shows the residual stress field in a beam with hardening surface by compression and pure bending. The results shown in Figures 6a and 6b (considering the location of the neutral axis in the centre of the beam's height) led to observing the change in residual stress field axisymmetric distribution for previous loading history. Results obtained from FEM (Urriolagoitia-Sosa, 2005; Molina-Ballinas, 2010; Urriolagoitia-Sosa *et al.*, 2010c), shown in Figure 6 for both cases (with and without loading history) validated the CCM.

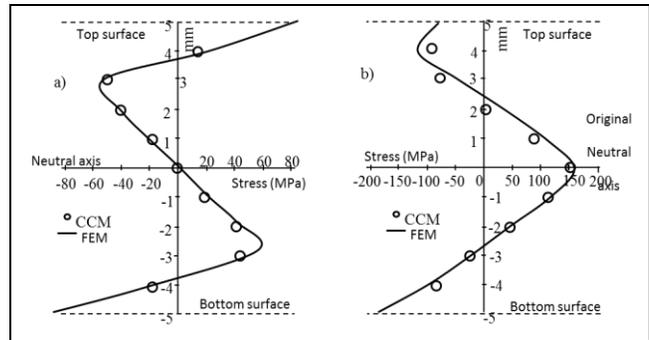


Figure 6. Residual stress field in beams. a) Specimen lacking prior loading history, b) Specimen with previous loading history

Pressurised pipe

The second analysis involved a sample of X42Cr13 steel pipe; this type of metal is mainly used in the petroleum industry (Figure 7a). A section of this pipe was obtained which had been used in service conditions for transporting petrochemical fluid.

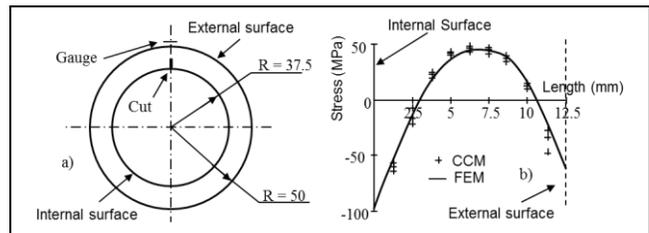


Figure 7. Residual stress field in the pipe. a) Specimen dimensions, b) Residual stress field obtained in the pipe

Even though the effects of service condition could not be fully determined, it was thought that internal fluid pressure in the pipe could have induced a residual stress field. The pipe sample was cut to obtain 15 mm thickness specimens having ring geometry. Three specimens were instrumented with strain gauges (Figure 7a) and an electro-erosion cut was made. Twelve specimens were tested, each having a 1 mm length cut, and strain relaxation was recorded at the end of each test. The CCM could be used with the strain data obtained for determining the residual stress field acting in the pipe (Figure 7b). Likewise, results obtained by the FEM validated the CCM.

Modified SEN specimen

The effect caused by a residual stress field in a component having

stress concentration and then inducing a residual stress field produced cracked component behaviour. A modified SEN specimen was used for experimental analysis (Figure 8a).

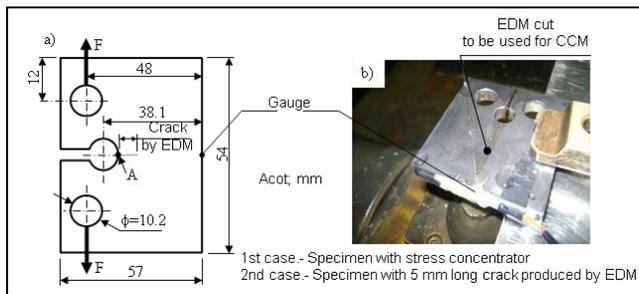


Figure 8. Modified SEN specimen. a) Tensile load application, b) Implementing EDM

AISI 316L stainless steel was selected for this research. The specimens were manufactured from 6.35 mm thick plate and a batch of 12 specimens was prepared. The material was annealed at 600°C for 30 minutes in an electric oven and left inside to cool down slowly (Romero-Ángeles, 2009; Urriolagoitia-Sosa et al., 2010a and 2010b). The specimens were separated into two groups of 6 units each. The first group was induced with a residual stress field by applying a tensile load in a servo-hydraulic machine. Tensile load was 10.5 kN (Figure 8a). The second group of specimens was prepared by introducing a 5 mm crack (Figure 8b) by electro-erosion (EDM). A residual stress field was then induced in the specimens by applying a tensile load having the same magnitude as the previous case. All specimens were instrumented with strain gauges on one of the specimens' lateral faces. The strain gauge was used (after introducing the cut (crack)) to collect data using the CCM to determine the residual stress field acting on a specimen. 1 mm deep cuts were made (depending on the specimen, from the main stress concentration point (A in Figure 8a) or the crack tip). The cut was made up to 1 mm before reaching a specimen's lateral surface and preserving some structural integrity. Figure 9a shows the residual stress field obtained by experimental procedure in modified SEN specimens without a previous crack; Figure 9b shows the residual stress field in the modified SEN specimen with a previously induced 5 mm length crack, taking the crack tip as the beginning of the cut for using CCM. These two figures also give the FEM numerical simulation results.

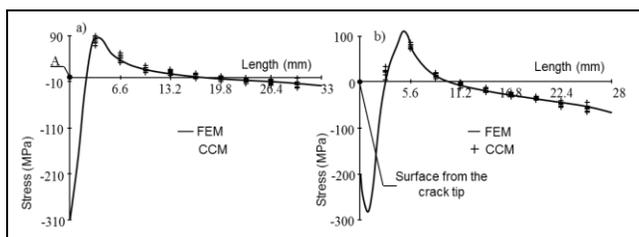


Figure 9. Residual stress comparison using modified SEN specimen. a) Specimen without crack, b) 5 mm length specimen

Discussion and Conclusions

The appearance of cracks in mechanical components has produced great interest for a long time now due to mechanical system deterioration, economic expense and possible human loss. Mankind has developed many means of combating the effects of deterioration caused by component cracking. It is evident that technologies strengthening a cracked component involve manipulating their physical properties by means of mechanical

processes (Hahn and Kanninen, 1980). As such, inducing residual stress fields is of the utmost importance as this can strengthen a material's resistance, promoting no failure nucleation and delaying crack propagation (Green, Tandon and Sglavo, 1999). Nevertheless, residual stresses are self-equilibrated (as tensile and compressive stress coexists) making their application and measurement an extremely difficult issue.

This paper has analysed the results of three study cases where residual stress fields were induced. Even though such cases were only theoretical, they ascertained manipulating mechanical processes for inducing a beneficial residual stress field for strengthening a material's mechanical behaviour. They were diverse as were the mechanical processes which would propitiate beneficial residual stress field in a particular component.

Figure 6a shows that an axisymmetric residual stress field was induced in bent beams, even though the benefits this kind of field could bring to the material could not be determined. When beams having characteristics such as those in the previous study were submitted to strain hardening by applying an axial compressive load, it could be observed (Figure 6b) how the residual stress field lost its axisymmetry and a large area had compressive stress on both component surfaces. It may be concluded that compressive residual stress tended to reduce crack propagation probability (Löhe, Lang and Vöhringer, 2002), since the tensile effect (causing a material's deterioration) would have to overcome the compression effect induced by the stress field. It could also be observed that the tensile area became reduced, meaning that the mechanical process applied in experimental analysis was beneficial for a component's service life (Urriolagoitia-Sosa, 2005). Experimental analysis was validated by the FEM (Urriolagoitia-Sosa, 2005).

The service effect acting on a riser by inducing a residual stress field was determined in the second study case, considered to be fatigue set up in the mechanical component. CCM led to determining residual stress field distribution and magnitude and the possible benefit from inducing residual compressive stress on the pipe's surface. It is worth mentioning that tensile residual stresses are located at the centre of a specimen and may not be considered as detrimental since cracks usually nucleate and propagate from the surface of an element. Figure 7b clearly shows the compressive residual stress field present on the pipe's transverse surface plane; this could have prevented crack nucleation and its possible propagation. Such compressive residual stress field could also be found on the pipe's internal surface within the component's fatigued area, having greater magnitude than that on the external surface. Fatigue when removing the pipe was most probably strengthening both surfaces. Nevertheless, it was obvious that the fatigue effect of major service cycles would eventually damage the material and cause the pipe to fail. Once again, numerical analysis simulated the pipe's working conditions to validate this research.

Analysis focused on two considerations for a modified SEN specimen in the last case study to visualise the positive effects obtained by strain hardening when an applied load exceeded the material's yielding point, followed by removing the load. This was done on two types of specimen: one with stress concentration and one where a crack was introduced. Compressive residual stress was generated in both cases at the surface near point A and the crack tip. Figures 9a and 9b show the material's increased mechanical resistance in both cases. Such increased

mechanical resistance was due to the compressive residual stress field, indicating that the component's tensile reloading had first to pass over the compressive stress to produce tensile stress and damage. This implied that the element could support a major tensile effect before cracking would occur. Nevertheless, such geometry and study case need to be extensively analysed, since a crack and possible propagation increases risk when applying the component (Molina-Ballinas, 2010; Urriolagoitia-Sosa et al., 2010c; Brandes, 1992).

This work has proposed a methodology for mechanically manipulating materials' properties and geometry to strengthen resistance to cracking or damage. The crack compliance method's versatility and accuracy has also been demonstrated for determining residual stress fields, as well as its low cost and ease of application.

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Variables

A_i : coefficients to be determined
 B : body thickness
 C : crack function responds
 CCM : crack compliance method
 δ_a : crack length increase
 δ_{EM} : strain change at body surface
 δU : storage strain energy differential
 E' : generalised Young's modulus
 ϵ : strain
 F : virtual load
 K_I : stress intensity factor mode I
 K_{Irs} : stress intensity factor mode I due to the residual stress field
 K_{IF} : stress intensity factor mode I due to a virtual load
 M : arbitrary point
 FEM : finite element method
 $\mu\epsilon$: microstrain
 n : polynomial series order
 P : load
 P_i : potential series
 s : distant from an arbitrary point
 t : crack longitude
 u : displacement

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