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Residual Stress Measurement of Quenched Components using Slitting Method

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Abstract: Residual Stress Measurement has gained interests among researchers for many years due to its great influence on the structural integrity. Slitting Method is one of the destructive techniques that relies on the introduction of an increasing cut to a part containing residual stresses. Similar to all other mechanical strain relief techniques, slitting also suffers from its shortcomings during the measurement procedure. In the present research, slitting method was simulated using finite element analysis. Furthermore, the experimental procedure of the slitting method was carried out. The quenching was employed to induce residual stresses within a sample made of 316L steel. A strain gauge was attached in the correct location and the residual stresses were measured using the compliance coefficients. The experimentally measured stresses were then compared with those predicted using finite element analysis. A very good correlation was observed.

Keywords: Slitting Method, Residual Stress, Compliance Coefficient, Quenching Process

1. Introduction

Residual stresses are stress fields that exist in the absence of any external loads. All mechanical processes can cause deformation that may lead to residual stresses [1]. Residual stresses play a critical role in failures due to fatigue, creep, wear, stress corrosion cracking, fracture, buckling and more [2]. Since residual stresses are a key factor in failure of engineering component, a correct knowledge of such stresses is of importance. Also Residual stresses are not always destructive. In some cases by inducing compressive residual stresses on the surface of a specimen, surface fatigue crack initiation has been postponed [3].

Residual stress measurement techniques are categorized into two main categories: destructive and non-destructive. All mechanical strain relief techniques rely on the concept that a part of specimen is machined away and the resulting deformations and strains are measured [4]. Then series of computations are utilized to compute residual stresses from the measured deformations or strains. Slitting method (or crack compliance) was originally proposed and extended by Cheng and Finnie [5], and then it has been extensively reviewed and developed by Prime [2]. In slitting a narrow cut of progressive depth is introduced into a part containing residual stresses and released strains are recorded by stain gauges attached on special locations [6]. The stresses can then be worked out from the strains. One way available in the literature is that the stress intensity factors are firstly achieved from released strains and then by using weight functions in a step by step solution, residual stresses are determined [7]. One advantage of this procedure is that stress intensity factors can be achieved without prior knowledge of residual stresses. A down side for this method is that the stress intensity factor and weight function which are crucial for residual stress determination are geometry dependent and not available except for simple geometries.

In the compliance method, the first responses of the specimen to a known applied load is obtained and called compliances. Then residual stresses are

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determined using an inverse solution [1]. For finding compliance coefficients finite element analysis is employed as a robust instrument that simplifies calculations.

Quenching is one of the heat treatment processes which are usually used to harden the engineering components and materials. It refers to the process of heating up a part to a certain temperature and then quickly cooling it down. Recently quenching has been employed to induce residual stresses within the engineering components as a reliable source of stress [8]. In this paper, also quenching was used to create residual stress within a beam sample.

2. Theory

Since there is no closed form solution for determination of residual stresses using measured strains, in an inverse solution an unknown residual stress field is estimated to be in a form of series expansion like Eq. (1).

$$\sigma_y(x)=\sum_{j=2}^{n}A_jP_J(x) \qquad (1)$$

In this equation P_j is Legendre polynomials basis and A_j represents the unknown amplitudes that the equation needs to be solved for. Therefore, the problem reduces to find the unknown amplitudes for determining residual stresses. Excluding constant and linear terms of Legendre polynomials guarantees to satisfy the moment and force equilibrium condition for estimated residual stress through the thickness of the specimen [9].

Considering compliance matrix, the unknown amplitudes are related to the measured strains. This matrix is formed by compliance coefficients as each array. Each compliance, C_{ij}, is the strain that would be measured if the exact known stress term in Eq. (1), P_j, is introduced to each cut depth, a_i. Using superposition principal, strains at each cut depth resulted from Eq. (1) can be written in the form of Eq. (2) [10].

$$\varepsilon_y(x)=\sum_{j=2}^{n}C_{ij}A_j \qquad (2)$$

Since a number of cuts made for strain measurement is more than the highest order of Legendre polynomial used for estimation, Eq. (2) is over determined. Therefore by using a least square fit which minimizes the errors between measured and fitted strains (obtained by Eq. (2)), the unknown coefficient are calculated by Eq. (3) [11].

$$A=\left[\overline{C}^T\times\overline{C}\right]^{-1}\times\overline{C}^T\times\tilde{\varepsilon}_{measureds} \qquad (3)$$

In this equation, the researchers adopt a matrix notation, with an upper-bar denoting a matrix and an upper-tilde denoting a vector where $\varepsilon_{measured}$ represents the ones obtained experimentally using strain gauge. It should be noted that the highest order Legendre polynomial used for estimation is determined through an error analysis which minimizes the differences between measured and fitted stains and considers model error as well [12].

3. Determination of compliance coefficients

There are some procedures for providing compliances like linear elastic fracture mechanic (LEFM) [13] and finite element [10]. In the present work finite element analysis was used for this purpose. Plane strain elements in quadratic order (CPE8) were utilized and due to symmetry about the cut plane, only half of the specimen needs to be modeled. Cuts were simulated by removing the symmetry displacement boundary conditions along the symmetry path which corresponded to the desired cut depth [10]. In each step a known term of Eq. (1) was applied on the required cut depth. Furthermore, compliances were achieved by recording the strains of node located where the strain gauge was attached at the experiment [14].

4. Cutting methods

Techniques for making the slots has evolved from sawing [15], milling [5] to electric discharged machining (Wire EDM) [16]. Sawing and milling are easier and cheaper to apply. However, the cutting may alter the original residual stresses through temperature increase and plastic deformation near the bottom of the cut. An accurate measurement of cut depth cannot be achieved when sawing is used. Furthermore, cutting into high compressive residual stress regions may pinch the cutter that terminates the measurement before the desired depth. Also to reduce the clamping force effect on measurement, clamping should be sufficiently away from the plane cuts. EDM makes the cuts without applying any forces, which minimizes the clamping force required for securing the specimen in the position.

In addition EDM can precisely determine depth of made cuts and the cutting can be resumed after rethreading the wire if it breaks [1,2]. EDM has some important advantages in comparison with other two methods i.e.; it can produce finer cuts and also can cut much more gently and can make slots in hard materials as well [2]. Besides using EDM have some limitations like the specimen must be electrically conductive and also EDM is not portable [1]. In wire EDM, the wire is electrically charged with respect to the specimen. As the wire approaches the workpiece, a spark jumps the gap and melts the material locally. This process occurs in deionized water [2].

5. Experiment

A beam shape sample was made of stainless steel 316L with dimensions of 40×45×65 mm^3. For quenching the specimen was heated up to 400°C in the furnace and then abruptly cooled down in water. To measure through thickness residual stress only a back face strain gauge was sufficient. The location of the back face strain gauge is illustrated schematically in Fig. 1. In this Fig., l is strain gauge active length and s is considered as the distance between center of the strain gauge and center of the slot.

A strain gauge of 1.57 mm length was attached on the face exactly opposite of the cut (s=0). Special care must be taken for installing the strain gauge in a way that the alignment arrows of strain gauge locate exactly along the slot. In the present study wire EDM with 250 µm diameter of wire was used for cutting. As it was mentioned earlier, the cutting procedure was performed in water tank of wire EDM which necessitated the strain gauge to

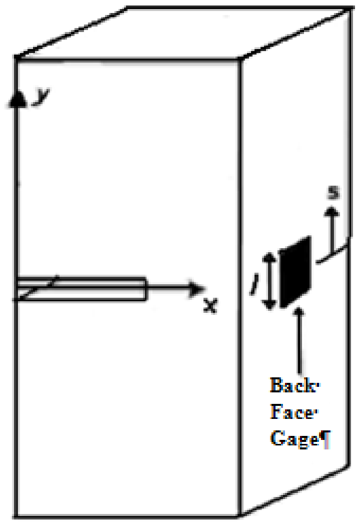

Fig. 1. Strain gauge location [13].

be waterproofed. In Fig. 2 the location of the installed strain gauge and in Fig. 3 coating due to water proofing the gauge through submersion are shown respectively.

After these preparations, the specimen was ready for cutting. The wire moved forward incrementally and after each cut a moment had to be waited for the strain readings stabilization within 1-2 microstrain. The cutting process was continued up to 95-98 % of the thickness of the part since after that the adverse effect of specimen's weight on strain readings invalidates the obtained data [2]. The released strain versus each cut depth achieved experimentally is shown in Fig. 4.

6. Results and discussion

First, the quenching process was simulated using finite element (FEM) analysis and then the residual stresses as a result of quenching were obtained. Then, all steps in the slitting method were simulated. For this purpose in the quenched component cuts were introduced in the model by removing elements at each step and released strains were obtained. By calculating compliance coefficients and forming compliance matrix residual stresses were determined by simulation of slitting and compared with finite element simulation of quenching process. Results are shown in Fig. 4.

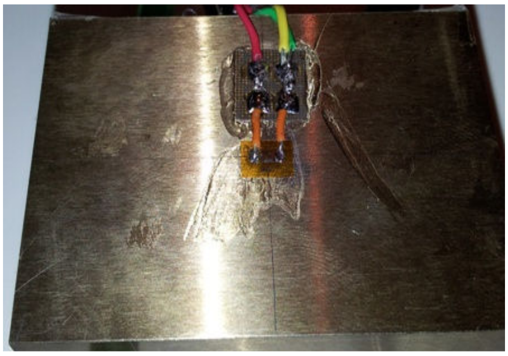

Fig. 2. Installed strain gauge on the back face.

Fig. 3. Coating of stain gauge.

By forming compliance matrix according to theory section and using strains recorded from experimental test, the unknown amplitudes, A_j, of Eq. (1) was estimated through Eq. (3). By finding the amplitudes A_j, estimated residual stresses were achieved. It should be noted that the highest order used in estimation was selected after an error analysis [12]. For verifying the accuracy of stress distribution estimated by slitting, it was compared with residual stresses achieved numerically as a result of quenching process in FEM. As it is illustrated in Fig. 6 the agreements are very good. Comparing Fig. 5 with Fig. 6 reveals that the simulation of slitting technique in a quenched specimen agrees with the experiment. The ability of simulating slitting method can be a robust procedure for extending this technique as it is a powerful tool to understand what actually happens during the experiments.

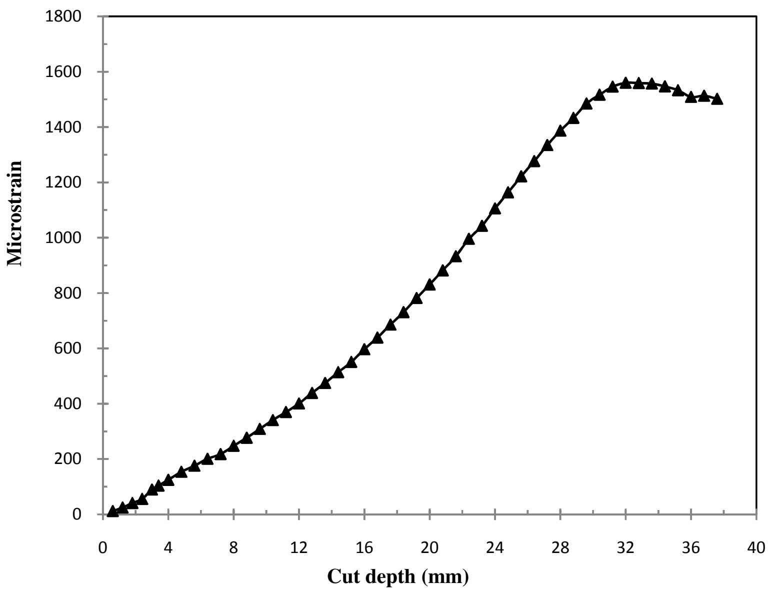

Fig. 4. Released strain during experimental cutting.

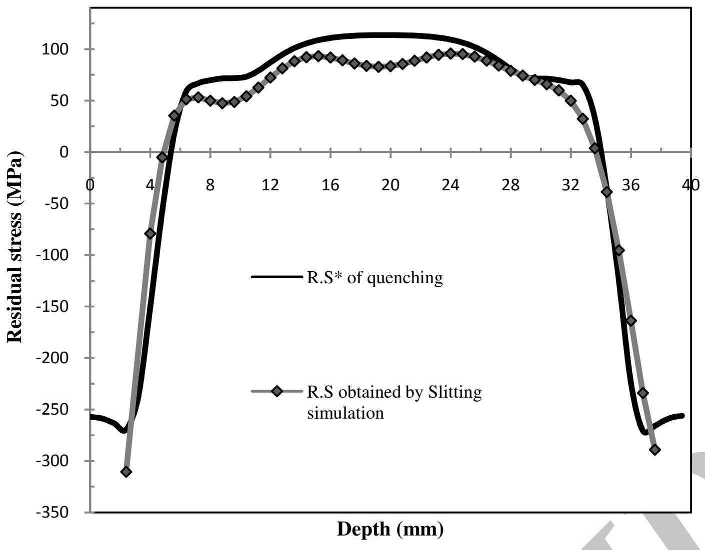

Fig. 5. Finite element simulation of quenching process and Slitting.

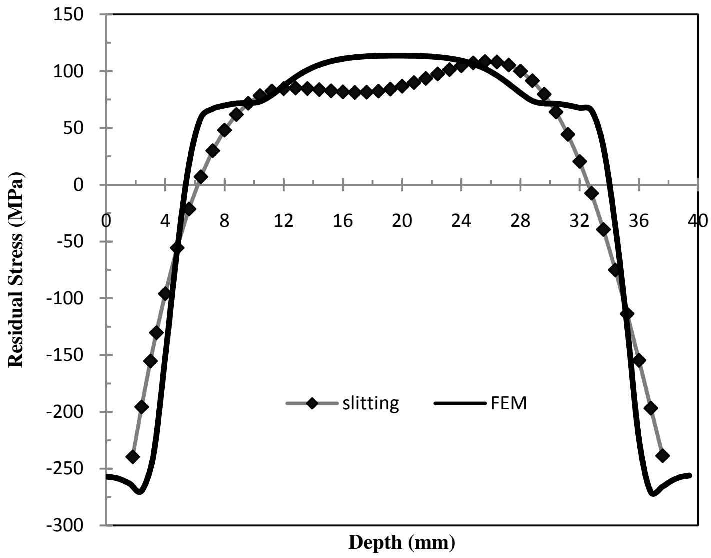

Fig. 6. Estimation of residual stress of quenching by slitting.

Conclusions

The results reveals that the simulation of slitting technique in a quenched specimen agrees with the experiment. The ability of simulating slitting method can be a robust procedure for extending this technique and investigating the vague aspects of the procedure such as plasticity. The results also indicate that the slitting technique can have a good precision for residual stress measurements deep inside the engineering components.

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