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Stress Variations Effect on the Accuracy of Slitting Method for Measuring Residual Stresses

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ABSTRACT

To maintain the structural integrity of the engineering components, having an exact knowledge of residual stresses is important. Among all mechanical strain relief techniques to measure residual stresses, slitting is one of the youngest. This technique relies on the introduction of a narrow slot of increasing depth in a part containing residual stresses. Similar to other measurement techniques, slitting also employs simplifying assumptions. One of these assumptions is that the stress does not vary along the cut line. There are many sources of errors in the slitting method. However, the error caused by this assumption can be severe. In this research, residual stresses of quenched samples were measured experimentally using slitting technique. The results were then compared with those obtained from the finite element analyses. The cylindrical specimens were designed with different ratios of height to diameter to investigate the effect of stress variations in transverse direction along the cut plane. It was evident that the non-uniformity of stress can severely influence the residual stresses measurement. The experimental results confirmed the numerical findings.

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1. INTRODUCTION

Residual stresses are the stress fields which are present in the absence of any external loads while they are in equilibrium. All manufacturing and heat treatment processes can induce residual stresses within the components. Residual stresses have a significant contribution to failure of engineering parts due to fatigue, creep, wear, stress corrosion cracking and more while in some cases it is intentionally induced in some parts [1]. Therefore, a good design procedure is the one that residual stresses have been accounted for [2, 3]. There are many techniques available in the literature to measure residual stresses [4]. Measurement techniques are mainly categorized into two groups of non-destructive and destructive techniques. All mechanical strain relief techniques (MSR) i.e. slitting, contour, center hole drilling, deep hole drilling and ring core, are grouped under destructive techniques in which a part of a specimen is machined away. The removed region of material containing residual stresses result in deformation. This deformation is then used to calculate original residual stresses in the component [5, 6]. Although, in semi destructive techniques only a small amount of component is removed leaving its overall structural integrity intact, destructive techniques compromise the structural integrity of the specimen.

In slitting a narrow cut of increasing depth is introduced into a part containing residual stresses and the resulting strains are measured using strain gauges attached at appropriate locations. Then, residual stresses are determined from the measured deformations by series of calculations [7, 8]. This procedure requires sets of coefficients, called compliances, to be determined. These coefficients can be obtained using fracture mechanics solutions and finite element method [1]. Some researchers [5, 9] employed fracture mechanics to calculate compliances and determined the residual stresses using an inverse solution. Ritchi and Leggat [10] used finite element analyses to obtain compliances for the first time. Schindler et al. [11] employed a series

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of mathematical relations based on linear elastic fracture mechanics to obtain stress intensity factor from the measured strains. They then determined residual stresses using a recursive relation and the data of the previous slot depth [6]. Advantage of this technique was that the stress intensity factor (SIF) can be determined without prior knowledge on distribution of residual stresses in the part. Slitting has currently turned into one of the most reliable measurement techniques because of its applicability in measuring wide range of materials including amorphous metals [12], functionally graded materials [13], ceramics [14] and composites [15] near surface and through thickness. A novel method has also been proposed in the literature [16] for measuring residual stresses in plates. Slitting is also capable of measuring residual stress in two octagonal directions [17]. In addition, authors have recently proposed a new technique to measure residual stresses in two orthogonal directions simultaneously [18].

Cutting has been performed using saw, milling and Wire Electric Discharge Machining (wire EDM) [2]. Wire EDM has recently been used in most of the applications for introducing slots into components. There are advantages in using wire EDM in comparison with other cutting techniques. For instance, wire EDM is presumed not to induce significant stress through cutting process. It can also cut hard materials without difficulty that can be very difficult for other techniques. Furthermore, it can produce very fine cuts depending on the wire diameter. Applications of wire diameters varying from 100 to 250 μm for through thickness measurements have been reported [1].

Similar to other measuring techniques, slitting also benefits from simplifying assumptions. One of these assumptions is that stress in a specific depth does not vary along the cut line. Furthermore, it is assumed that the deformation due to cutting is linear elastic. Occurrence of plasticity is also stated as one of the potential source of error in most of other MSR techniques [19]. This is because the bases of all these procedures rely on elasticity relations. Where the applications violate these assumptions; errors would be inevitably associated with the measurement results. The later assumption has gained more attentions among slitting practitioners [17] compared to the former one. Slitting can only determine residual stresses along a path not on a surface. Therefore, the stress variation along the cut direction must be insignificant to minimize the error. In the present work, the effect of stress variation in transverse direction is investigated and interesting results are presented.

2. THEORY

The unknown residual stress is expressed in the form of a series expansion defined in Equation (1).

$$\sigma_y(x) = \sum_{j=2}^{n} A_j P_j \tag{1}$$

where A_j are the unknown amplitudes and P_j are the Legendre polynomials. The first two terms of Legendre polynomials are omitted from calculations as these two terms do not satisfy the moment and force equilibrium over the thickness of the specimen. Also n is the highest order of the Legendre polynomial used in the stress determination. Measured strains in a part containing residual stress were plugged in the equation as follows:

$$\varepsilon(a) = \sum_{j=2}^{n} A_j C_j(a) \tag{2}$$

where a is slot depth and $C_j(a)$ are called compliance coefficients. These coefficients were basically the measured strains when the exact term of Legendre polynomial of j^{th} order were applied to the slot of depth a.

$$C_j(a) = \varepsilon(a)\big|_{\sigma(x)=P_j} \tag{3}$$

Obtaining the unknown amplitudes required the measurement of strains in m depths when $m > n-1$. Since the number of measured strains was more than the unknown amplitudes, Equation (2) was over-determined. Therefore, Equation (2) was solved using least square fit (LSF) to minimize errors between measured and calculated strains. Adopting a matrix notation and applying LSF to Equation (2), Equation (4) was resulted which provided the unknown amplitudes.

$$A = [\overline{C}^T \times \overline{C}]^{-1} \times \overline{C}^T \times \tilde{\varepsilon}_{measured} \tag{4}$$

where $\tilde{A}$, $\tilde{C}$ and $\tilde{\varepsilon}_{measured}$ are considered matrices. Having the amplitudes A led to residual stress distribution using Equation (1) assuming compliance coefficients are known.

3. DETERMINATION OF COMPLIANCES

In the current research, finite element method was used to determine the compliances. As it is illustrated in Figure , due to symmetry, only half of the specimen was modeled. The mesh was refined near the cut plane ($x=0$) and the model contained around 6000 elements. Quadratic plane strain elements were employed to create the finite element model. Boundary conditions were defined on the cut plane restraining all nodes along x direction. Furthermore, the slot was simulated by progressively removing the symmetry boundary conditions along the cut path corresponding to the desired cut. To obtain the compliances in a specified depth, a known term of Legendre polynomials was applied to the slot [15].

4. EXPERIMENTS

The samples were made of 316L stainless steel. This stainless steel was selected so it had no phase transformation while quenching [20] as all austenitic stainless steel materials including 316L steel remain unchanged from ambient temperature to almost half the melting point due to consisting of alloy elements such as nickel and chrome. Tensile tests at different temperatures were carried out to determine the material properties of the employed steel and the results are shown in Table 1. The standard ASTM E8M was used.

Three cylinders with 60 mm diameter were manufactured. The heights of two cylinders were 60 mm and the third one was 90 mm. Quenching is one of the heat treatment procedures that is usually used to harden the materials. Quenching consists of heating up a part to a certain temperature and then quickly cooling it down. Recently quenching was employed to induce residual stresses within the engineering components [21]. In the present study, quenching was used to induce residual stresses into the cylinders. The temperature was measured in a specimen core using a thermocouple to determine the required time for the specimen to reach the target temperature.

Therefore, each specimen was left in the furnace at $300^{\circ}\mathrm{C}$ and $500^{\circ}\mathrm{C}$ for sufficient time in a way that material deep within the components reached the desired temperatures and then cooled down in room temperature water.

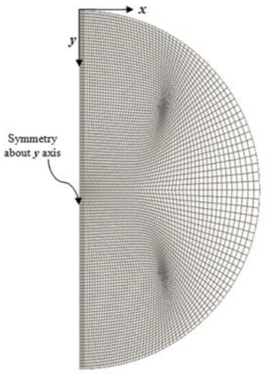


Figure 1. Finite element model for calculating compliances

TABLE 1. Mechanical properties of 316L stainless steel at different temperatures

Temperature (^{o}C)	**Young's modulus** (GPa)	**Yield stress** (MPa)
20	195	257
100	191	211
250	183	185.32
400	173	132

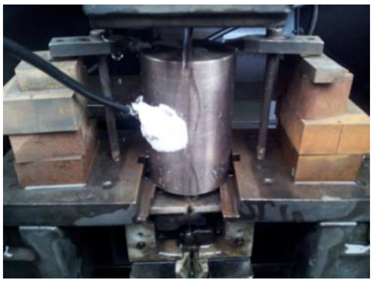


Figure 2. Cylinder of 90 mm height under cutting process.

A cooling rig was designed to spray water on the samples to perform a quick cooling stage. To prepare the specimens for residual stress measurement, the strain gauges were installed at the faces opposite to the slot. Wire electro-discharge machine was used to cut the samples. Wire with 250µm diameter was used to create the slots. In addition, it was necessary to seal the gauges while cutting as the water might cause the short cut in the strain gauge circuits. The slot was put into the component incrementally and the strains were recorded at each increment [22]. The test set-up and the specimen under cutting process is shown in Figure (see Figures 1 and 2).

5. NUMERICAL STUDIES

Measured residual stresses were compared with those obtained numerically. All simulations were performed using commercial code ABAQUS [23]. A three-dimensional finite element model was created. Partitioning model helped to refine mesh near the cut plane. The number of elements were about 65000 linear elements of the type C3D8R. Slitting procedure was also simulated following quenching. Due to having two symmetry planes, only a quarter of the specimen was modeled. Employing the quarter model reduced the CPU time dramatically. It also made possible to remove boundary conditions to simulate cuts instead of removing elements. For this purpose, boundary conditions on the cut plane was incrementally released corresponding to the depth of the cut. The released strains were then used to determine the original residual stresses. Proper mesh was constructed as shown in Figure 3.

6. RESULTS AND DISCUSSION

Figure 4 illustrates the experimentally measured strains against the cut depths. The strains for all three specimens are plotted. The calculated stresses are also illustrated in Figure 5 to Figure 7 for all three components. It should be noted that in these figures the results of residual stresses measurements and simulations of slitting method are compared. The figures also contain the residual stresses obtained from the simulation of quenching. It was evident from the results that the measurements in both 60 mm height cylinders were not satisfying. One of the potential causes of errors may be the plasticity which inevitably occurs during the cutting process. However, the extent of the plastically deformed regions was a key factor to judge the influence of plasticity.

In Figure 8, finite element models of two 60 mm height cylinders, that were quenched at 500 °C and 300 °C, are shown respectively. The missing sections in these figures are the elements with their Von-Mises stresses exceeded the yield stress at a randomly selected cut depth (here equal to 24mm) corresponding to the plasticity affected region. If the plasticity were the real cause of the error in estimations of the two samples, it could be expected that by decreasing the volume of plasticity in component quenched at 300 °C, the accuracy of the measured residual stresses improved. Although, the error in the cylinder quenched at 300 °C was slightly less than the other one, it was not completely removed considering that the plasticity affected zone was very small.

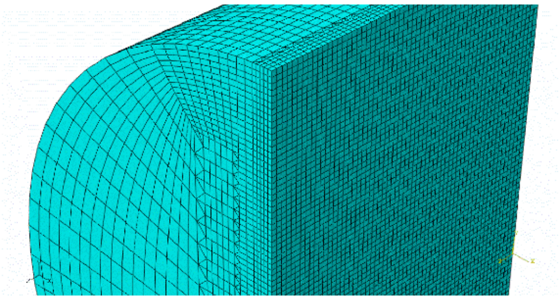


Figure 3. Mesh of the finite element model

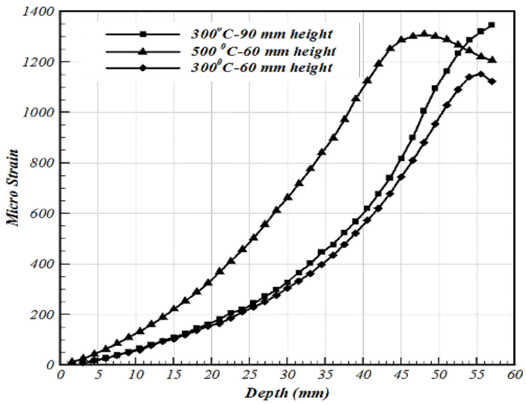


Figure 4. Experimental strains in three cylinders

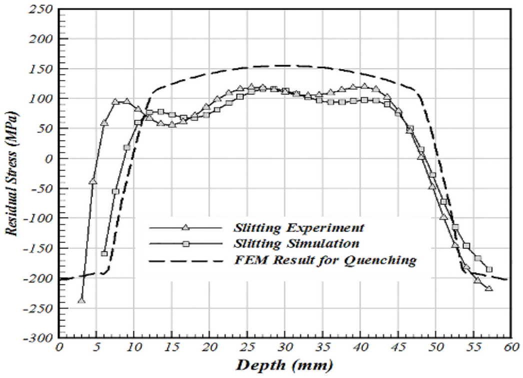


Figure 5. Cylinder with 60 mm height quenched at 500 °C

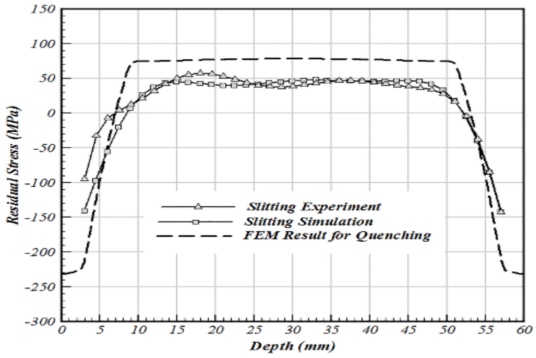


Figure 6. Cylinder with 60mm height quenched at 300°C

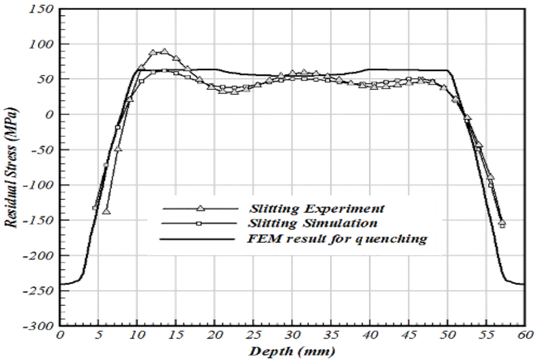


Figure 7. Cylinder with 90 mm height quenched at 300 °C

Therefore, it was logical to doubt that the plasticity could not be the main cause of the error. In contrast, measurement of the 90 mm cylinder quenched at 300 °C indicated promising results. Figure 6 illustrates that the accuracy of the residual stress measurement was improved in comparison with the other two samples (60 mm height cylinders). It is reminded that both cylinders were quenched at 300 °C and the only distinctive parameter between these two cylinders was their heights.

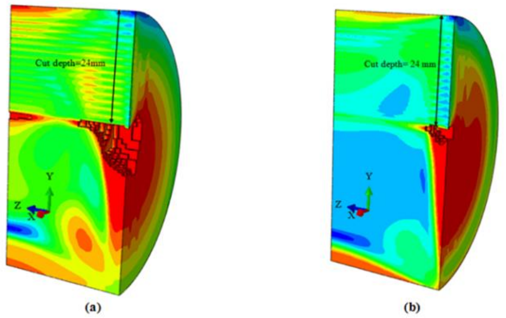


Figure 8. (a) Plasticity occurring in cylinder quenched at 500°C, 60 mm height and (b) plasticity occurring in cylinder quenched at 300°C, 60 mm height

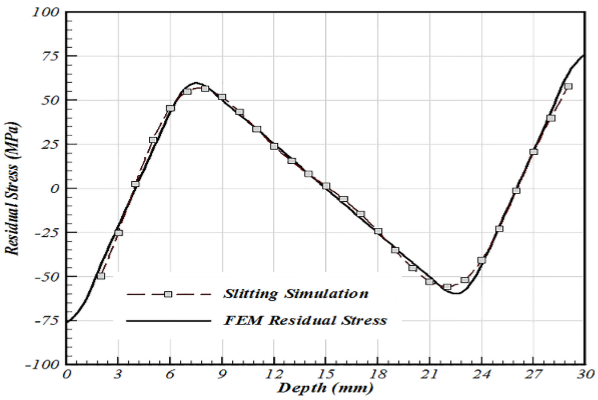


Figure 9. Residual stress estimation in 4-point bending by slitting simulation

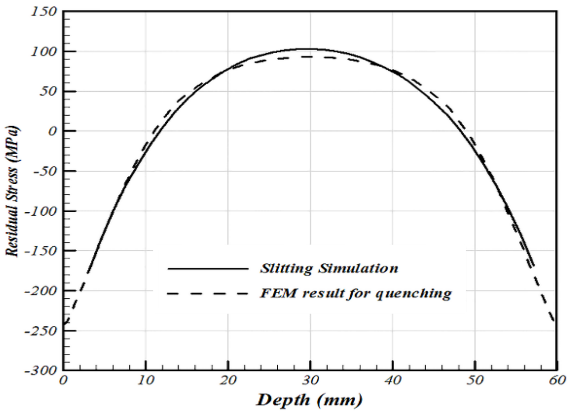
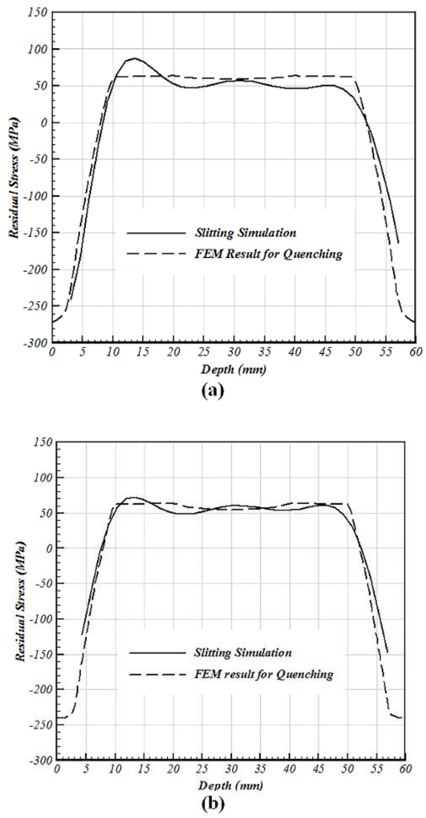


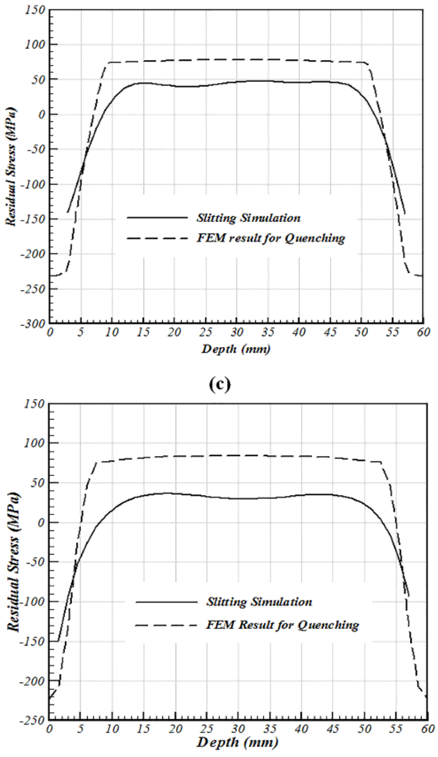
Figure 10. Residual stress estimation by slitting in a cylinder with plane strain assumption

To further dig the idea, the stress measurement by slitting method was modeled on two specimens, a 4-point bending sample and a quenched cylinder. In 4-point bending sample the basic assumption of the uniform stress distribution along a line in tensile or compressive region is definitely satisfied resulting in good accuracy in residual stresses measurement. The results of slitting simulation for this sample are shown in Figure 9. Good results were obtained.

Also simulation of slitting method was carried out on a quenched cylinder of 60 mm in diameter at $300^{o}C$. For the sake of satisfying stress uniformity along the cut line the cylinder was considered plane strain condition. However, this was not a valid assumption for the quenched cylinder and it was only done for the sake of the argument.

The results obtained from the slitting simulation for the plane strain model of the quenched cylinder are plotted in Figure 10. It can be seen from the results that simulations of both measurements led to very satisfying results with almost no error. More simulations were carried out for cylinders with different heights of 120, 90, 60 and 40 mm and all with 60 mm diameter quenched at $300°C$. The results are shown in Figure (a) to 11(d). It was concluded from the graphs that by decreasing the heights of the cylinders from 120 to 40 mm the accuracy of slitting method was also reduced. It meant that the higher height of cylinders resulted in less deviation from the original residual stresses. Therefore, as it was confirmed by simulations shown in Figure 11 (a) to (d) having more uniform residual stresses along the cut line resulted in better estimation of residual stresses by slitting method.





(c)

(d)

Figure 11. Simulation results of residual stress measurement by slitting in cylinder (a) 120 mm height, 60 mm diameter, (b) 90 mm height, 60 mm diameter, (c) 60mm height, 60 mm diameter and (d) 40mm height, 60 mm diameter

7. CONCLUSIONS

It is concluded that the simplifying assumption assuming uniform stresses along the cut line is not a valid assumption and could seriously affect the accuracy of the slitting results. Most of previous works that have practiced slitting are based on the 4-piont bending specimens that theoretically satisfy this assumption which is why this error has not been reported before.

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چکیده

به منظور حفظ یکپارچگی سازه ای در سازه های مهندسی اندازه گیری دقیق تنش‌های پسماند از اهمیت خاصی برخوردار است. روش‌های مخرب اندازه گیری تنش‌های پسماند به روش‌هایی گفته می‌شود که در آن قطعه بریده یا سوراخ می‌شود. از میان روش‌های مخرب اندازه گیری تنش‌های پسماند، روش شیارزنی یکی از جدیدترین روش‌های مورد استفاده است. در این روش یک شیار باریک که با عمق افزایشی، در قطعه حاوی تنش پسماند ایجاد می‌شود. در این روش نیز مانند سایر روشها از فرضیات ساده کننده‌ای استفاده می شود. یکی از این فرضیات این است که تنش در امتداد خط برش ثابت است. ایجاد خطا در روش شیار زنی علت های زیادی دارد ولی خطای ایجاد شده توسط این فرض ساده کننده می تواند بیشتر از دیگر علت‌ها باشد. تحقیق حاضر به بررسی این موضوع می پردازد. در این تحقیق از استوانه های کوئنچ شده برای ایجاد تنش پسماند استفاده می‌گردد. همچنین شبیه سازی انجام روش شیارزنی برای بررسی اثر تغییرات تنش در امتداد خط برش با استفاده از نرم افزار آباکوس انجام شده است. نمونه های استوانه ای با طول های مختلف برای ایجاد تغییرات تنش در امتداد خط برش ساخته شده است. نتایج بدست آمده نشان داد که ثابت نبودن تنش می تواند خطاهای بزرگی در اندازه گیری تنش پسماند ایجاد کند. نتایج بدست آمده از اندازه گیری های تجربی نتاج شبیه سازی ها را تائید کردند.

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