Method for Measuring Residual Stresses Induced by Boring in Internal Surface of Tube and Its Validation with XRD Method

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Abstract: Residual stresses can have a strong effect on the usability of machined parts, and the X-ray diffraction (XRD) measuring equipment, which is commonly used to measure residual stresses, is very expensive. This paper presents a method of measuring the residual stresses induced by boring in the internal surface of a tube with much cheaper equipment. The method, called the strain-based method is mainly based on the strains measured on the external surface of the tube. It is proposed on the basis of the very long tube assumption. The finite element method (FEM) analysis is thus used to validate the length of the tube. Guided by the FEM results, an appropriate length of the tube is chosen, and the residual stresses are obtained from both the strain-based method and the XRD method. Stress profiles obtained from both two methods are compared. The comparison result indicates that the profiles of the two methods agree well with each other. Therefore, it can be concluded that the accuracy of the strain-based method is high enough, and it can be applied to residual stress measurement in practice.

Key words: residual stress; finite element method (FEM); strain; element birth and death; X-ray diffraction (XRD)

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1 Introduction

Residual stresses exist in most parts after machining, whose values are hard to accurately measure in most cases. Metal cutting is a process with high temperature, high strain, high strain rate, and large elastic-plastic deformations[1-2], and residual stresses exist in the superficial layer, whose depth is commonly no more than 0.2 mm. However, the gradient in the thin layer is very high along the depth direction. The residual stresses can be attributed to several factors such as mechanical stresses, thermal stresses and phase transformations[3-4]. The residual stresses induced by machining in the surface layer are an important factor that affects the workpieces statics strength, fatigue strength, corrosion resistance, service life, geometric and dimension stability[5-7]. Wang, et al.[8] studied the deformations caused by residual stresses generated by milling in aluminum alloy, and Miao, et al.[9] improved the surface property by shot peening. Generally speaking, the residual stresses play an important role in in-service performance of machined parts. Therefore, it is significant to measure the residual stresses induced by machining and reduce their harmful effects.

During the past years, different methods for measuring residual stresses have been developed. They can mainly be classified as destructive, semi-destructive and non-destructive techniques[10]. The destructive and semi-destructive

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techniques, called mechanical methods, are dependent on inferring the residual stresses from the displacement measured after completely or partially relieving the stresses by removing material[11]. Sectioning, contour, hole-drilling, deep-hole and ring-core are the principal destructive and semi-destructive techniques used to measure the residual stresses in structural members[10-11]. Non-destructive techniques include neutron or X-ray diffraction, magnetic methods and ultrasonic methods. These techniques usually measure some parameters related to the stresses[12-15]. X-ray diffraction (XRD) method is commonly used to measure the surface residual stresses, as the penetration depth of X-rays in common metals is very shallow (just few microns). A layer removal technique must thus be used in association with XRD method to measure in-depth stresses. It is recognized that the XRD equipment is very expensive, and the XRD method is just applicable to materials that are crystalline and relatively fine grained[16], which are serious drawbacks. Therefore, this paper presents a strain-based method using much cheaper equipment to measure the residual stresses induced by boring in internal surface of the tube. The correctness of the strain-based method will be validated by the results obtained from the XRD method later in this paper.

2 Calculation Principle

The theory of calculating residual stresses in the internal surface of tube is based on the variations of the axial length and the external diameter when removing the internal stress layers, which was first presented by Mesnager in 1919[15]. Authors improve the calculating method and put it into practice here.

Assuming that the tube is so long that it can be disposed as a problem in a plane (an appropriate length of the tube will be determined by finite element method (FEM) in what follows). The internal radius of the tube is R_{IN}, and the external radius R_{OUT}. σ_Z, σ_T, σ_R are the stresses along the axial, tangential and radial directions in the tube, respectively. A schematic representation of the residual stresses in the tube is shown in Fig. 1.

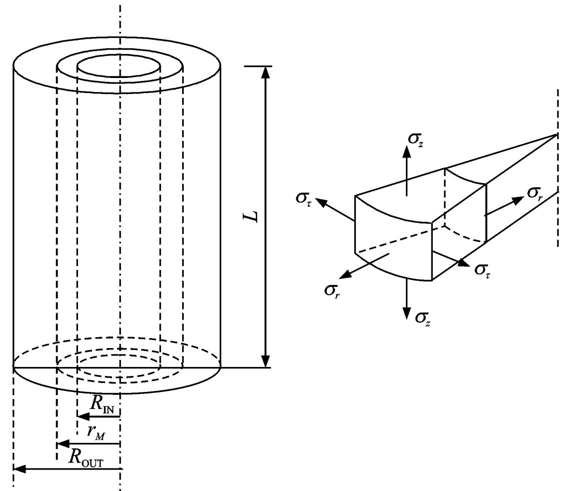


Fig. 1 Schematic representation of the residual stress in tube

The average value of the residual stress in the layer from radius R_{IN} to radius r_M is $\sigma(r_M)$. When removing this layer, it equals to applying the force of the same magnitude in the reverse direction on the newly exposed surface of the rest part after the layer removal. Here σ_{ZO}, σ_{TO} and σ_{RO} are the stresses along the axial, tangential and radial directions on the outside surface induced by the internal layer removal. There is no force on the internal surface in the radial direction before layer removal, and thus σ_{RO} is 0. According to the Lame cylinder theory, it can be concluded that

$$\sigma_{TO}=\frac{2r_M^2}{R_{\mathrm{OUT}}^2-r_M^2}\sigma_R(r_M) \quad (1)$$

Let ε_{ZO}, ε_{TO}, ε_{RO} represent the strains along the axial, tangential and radial directions on the outside surface. The relationship between the stresses and the strains on the external surface is as follows

$$\sigma_{ZO}=\frac{E}{1+\mu}\left[\varepsilon_{ZO}+\frac{\mu}{1-2\mu}(\varepsilon_{ZO}+\varepsilon_{TO}+\varepsilon_{RO})\right] \quad (2)$$

$$\sigma_{TO}=\frac{E}{1+\mu}\left[\varepsilon_{TO}+\frac{\mu}{1-2\mu}(\varepsilon_{ZO}+\varepsilon_{TO}+\varepsilon_{RO})\right] \quad (3)$$

$$\sigma_{RO}=\frac{E}{1+\mu}\left[\varepsilon_{RO}+\frac{\mu}{1-2\mu}(\varepsilon_{ZO}+\varepsilon_{TO}+\varepsilon_{RO})\right] \quad (4)$$

where E and μ are the elasticity modulus and poisson ratio of the material, respectively. As σ_{RO} is 0, it can be obtained by

$$\varepsilon_{RO}=-\frac{\mu}{1-2\mu}(\varepsilon_{ZO}+\varepsilon_{TO}+\varepsilon_{RO}) \quad (5)$$

From Eqs. (1,3,5), another equation can be written as

$$\sigma_R(r_M)=\frac{E}{1-\mu^2}\frac{R_{\mathrm{OUT}}^2-r_M^2}{2r_M^2}(\varepsilon_{TO}+\mu\varepsilon_{ZO}) \quad (6)$$

Moreover, the axisymmetric plane equilibrium should be satisfied, i. e.

$$\frac{\mathrm{d}\sigma_R}{\mathrm{d}r_M}+\frac{\sigma_R-\sigma_T}{r_M}=0 \quad (7)$$

If there is no external force applied to the part, the equilibrium equations along the axial and tangential directions should be satisfied as follows

$$\int_{R_{\mathrm{IN}}}^{R_{\mathrm{OUT}}}\sigma_Z 2\pi r\mathrm{d}r=0 \quad (8)$$

$$\int_{R_{\mathrm{IN}}}^{R_{\mathrm{OUT}}}\sigma_T\mathrm{d}r=0 \quad (9)$$

The residual stress along the tangential direction can be obtained from Eqs. (6,7)

$$\sigma_T(r_M)=\frac{E}{1-\mu^2}\left[\frac{(SR_{\mathrm{OUT}}-S)\cdot\mathrm{d}(\varepsilon_{TO}+\mu\varepsilon_{ZO})}{\mathrm{d}S}-\frac{SR_{\mathrm{OUT}}+S}{2S}(\varepsilon_{TO}+\mu\varepsilon_{ZO})\right] \quad (10)$$

In Eq. (10), $SR_{\mathrm{OUT}}=\pi R_{\mathrm{OUT}}^2$, $S=\pi R_M^2$. When the internal layer from radius R_{IN} to radius r_M has been removed, the residual stresses in the rest part can be assumed to be redistributed uniformly. Based on this assumption and Eq. (8), another equilibrium equation can be obtained

$$\int_{R_{\mathrm{IN}}}^{r_M}\sigma_Z 2\pi r\mathrm{d}r=\pi(R_{\mathrm{OUT}}^2-r_M^2)\sigma_{ZO}(r_M) \quad (11)$$

Taking a derivative with respect to r_M of Eq. (11), we have

$$\sigma_Z=\frac{R_{\mathrm{OUT}}^2-r_M^2}{2r_M}\frac{\mathrm{d}\sigma_{ZO}}{\mathrm{d}r_M}-\sigma_{ZO} \quad (12)$$

The residual stress along the axial direction can be derived from Eqs. (2,5,12)

$$\sigma_Z(r_M)=\frac{E}{1-\mu^2}\left[\frac{(SR_{\mathrm{OUT}}-S)\cdot\mathrm{d}(\varepsilon_{ZO}+\mu\varepsilon_{TO})}{\mathrm{d}S}-(\varepsilon_{ZO}+\mu\varepsilon_{TO})\right] \quad (13)$$

In conclusion, the residual stresses in three directions induced by boring in the internal surface of the tube can be obtained from Eqs. (6,10,13).

3 FEM Validation of Tube Length

The aforementioned equations are deduced on the very long tube assumption, but in practice it is not the case. For the convenience and accuracy of the measurements, FEM is used to find an appropriate length of the tube in this paper.

The tube model, created by Abaqus 6.10 software, has a 45 mm external diameter and a 41 mm internal diameter. As presented in Ref.[2], when the length of the tube is over 6 times of the external diameter, the measurement accuracy will be high enough. Here the length of the tube is first set as 450 mm to ensure a very high accuracy. Since the residual stresses along the radial direction are so small in a real part that they can be ignored in the model, the model is just loaded with the residual stresses along the axial and tangential directions. Here an input file calculated by MATLAB is used to load the residual stresses, and the stress values in the cylindrical coordinate should be transmitted to the rectangular coordinate with the following equation

$$\begin{Bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \tau_{xy}\end{Bmatrix}=\begin{Bmatrix}\cos^2\theta & \sin^2\theta & -\sin2\theta\\ \sin^2\theta & \cos^2\theta & \sin2\theta\\ 1/2\sin2\theta & -1/2\sin2\theta & \cos2\theta\end{Bmatrix}\begin{Bmatrix}\sigma_\rho\\ \sigma_\theta\\ \tau_{\rho\theta}\end{Bmatrix} \quad (14)$$

With the command "initial conditions, type=stress, input=S.dat", the stress file is imported. Here the residual stresses applied to the model can be seen as a typical case of residual stresses induced by boring.

After loading the residual stresses (Fig. 2), the gradient of the stresses along the depth direction is extremely high, which is the main characteristic of the residual stresses induced by machining. To simulate the experimental process of removing material layers by corrosion, the technology of "element birth and death" is used to "kill" the elements in the internal surface of the model layer by layer. The strains on the outside surface along the axial and tangential directions are recorded after "killing" each layer. Here the recorded strains are in the mid-height of the model. In the experiments, the strain gauge should also be installed in the mid-height of the tube.

The accuracy of the results obtained from the above model is high. But the tube is too long, thus causing lots of inconvenience and material

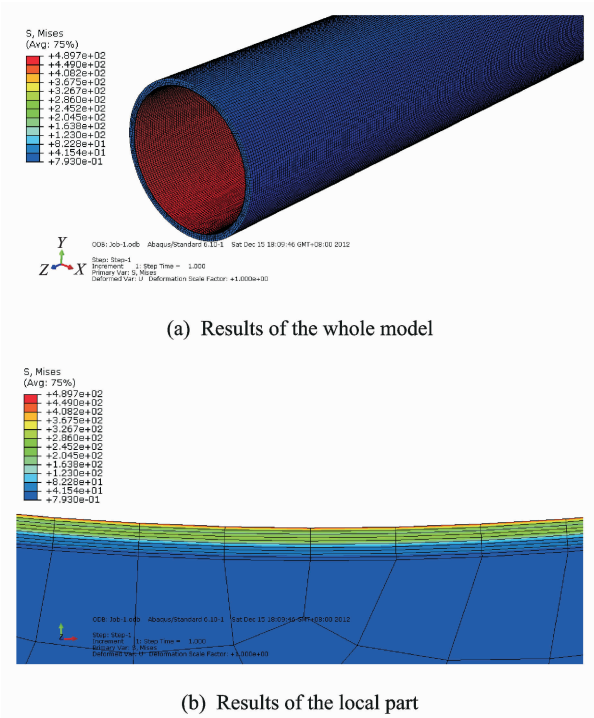


Fig. 2 Results of the model after imposing residual stress

wastage. A new model with the same internal and external radii is created to have a different length along the axial direction. The strains obtained from the long model mentioned above is set as references to see how long the new model should be in order to gain accurate results.

Here, Python language is used to create the model and make the second development to Abaqus. The tube length is first set as 20 mm. The tube length is increased by an increment of 5 mm each time. The calculated strains and the references are compared to find out whether the accuracy is high enough. Fig. 3 gives a schematic representation of the second development, where the high accuracy is defined as that the maximum error is no more than 0.1×10^{-6}.

The analytical result indicates that when the tube length reaches 50 mm, the accuracy can meet the requirement. Therefore, it can be concluded that the 50 mm tube length is long enough to obtain an accurate result. The result can give some guidance to the related projects in practice, that is, as the tube diameter changes, if the ratio of tube length to external diameter is no less than $\lambda=50/45=1.11$, the accuracy will be high enough.

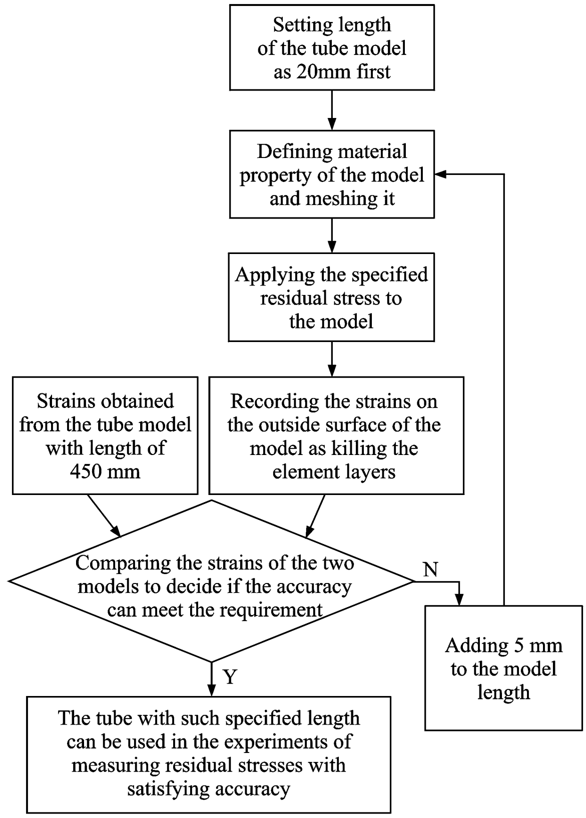
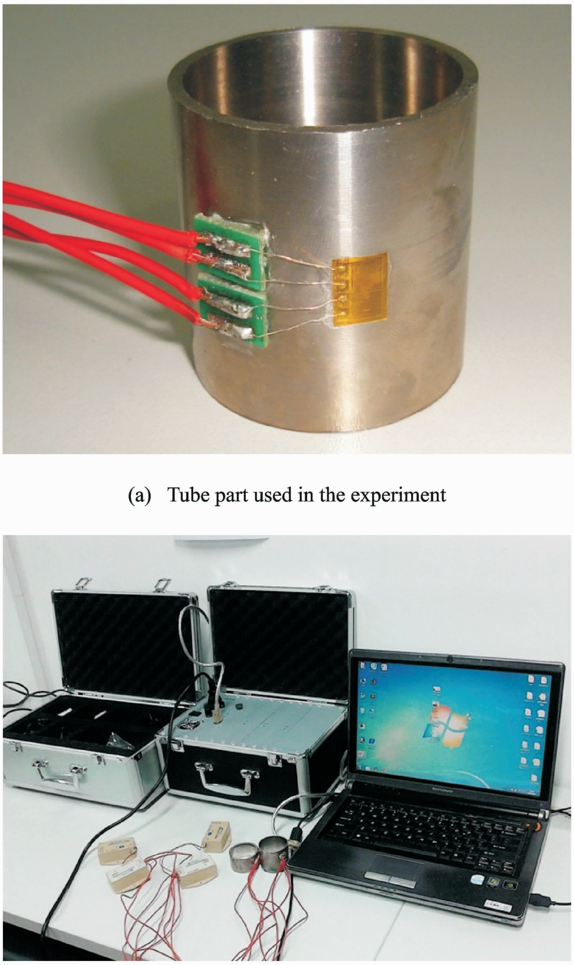


Fig. 3 Schematic of the second development

4 Validation of Strain-Based Method with XRD Method

To validate the correctness of the strained-based method, a comparison should be made between the results obtained from the strain-based method and those from XRD method.

The tube used in experiments (Fig. 4(a)) is made of Ti6Al4V. First, annealing treatment is performed on the tube to remove the initial residual stresses. The external and internal diameters are 50 mm and 41 mm, respectively. The internal material layers are removed by chemical corrosion which will not introduce any new residual stress to the rest part. According to the relationship between the depth of the removed layer and corrosion time, the time should be precisely controlled to make sure that for each time the depth of the removed layer is 10 μm. After finished corrosion, the chemical reagent is washed away immediately. When the tube reached the room temperature, the strains in the tangential and axial directions are recorded. Since temperature has a significant



(a) Tube part used in the experiment

(b) Strain meter equipment

Fig. 4 Tube to be measured and the strain meter equipment

effect on the measuring results, and the room temperature cannot always stay the same, temperature compensation must be accomplished here. After each layer removal and the corresponding strains recording, the residual stresses on the internal surface of the tube are also measured by the XRD method, using a portable Proto-LXRD machine and employing the following parameters: tube voltage of 30 kV, tube current of 25 mA, irradiated area of 1 mm×3 mm and the $\sin^2\varphi$ method.

Removing the stress layers surely causes some relaxation and redistribution of the residual stresses, and thus the results from the XRD method should be compensated in order to obtain correct stress values.

After Moore and Evans published their paper in 1958, few literatures can be found on the development of correction method for layer removal[17-18]. The correction method proposed by Moore and Evans for plates and cylinders is still the most commonly used one, that is

$$\sigma_T(r_M)=\sigma_{TM}(r_M)+\left(\frac{r_M^2+R_{IN}^2}{r_M^2-R_{IN}^2}\right)\sigma_R(r_M) \quad (15)$$

$$\sigma_R(r_M)=-\left(1-\frac{R_{IN}^2}{r_M^2}\right)\int_{r_M}^{R_{OUT}}\left(\frac{r\sigma_{\theta M}}{r^2-R_{IN}^2}\right)\mathrm{d}r \quad (16)$$

$$\sigma_Z(r_M)=\sigma_{ZM}(r_M)-2\int_{r_M}^{R_{OUT}}\left(\frac{r\sigma_{zm}(r)}{r^2-R_{IN}^2}\right)\mathrm{d}r \quad (17)$$

where σ_T, σ_R, σ_Z are the corrected circumferential, radial, axial stresses, respectively. σ_{ZM} and σ_{TM} are the measured residual stresses in the axial and tangential directions, while R_{OUT}, R_{IN} and r are the external, internal and actual measurement radii, respectively.

Eqs. (15—17) are based on several assumptions: (1) Circumferential layer removal should not introduce any new residual stress to the rest of the part. It is well-known that corrosion will not cause any new residual stress, and the material layers are thus removed by chemical corrosion here. (2) The tubes to be measured must be long enough and the measurement location should be far away from the edges. In this paper, the tube used in the experiments is not very long, just 50 mm. According to the finite element analysis, the accuracy is acceptable when the measurement is performed in the middle height of the tube. (3) The residual stresses to be measured are either plane symmetric or rotationally symmetric[18]. Here in this paper, the residual stresses induced by boring is highly rotationally symmetric. (4) During the relaxation and redistribution caused by layer removal, the stresses must always remain elastic. In our experiments, the residual stresses induced by boring are certainly far from elastic limit of the material. Hence, it will not cause any plasticity during relaxation and redistribution.

In general, these assumptions are all satisfied here. Therefore, the measured residual stress can be corrected by Eqs. (15—17).

5 Results and Discussion

The residual stress profiles obtained from two methods are shown in Fig. 5. The residual stresses in the axial and tangential directions induced by boring are all compressive in the outmost layers. The magnitude of the stress along the tangential direction is greater than the one along the axial direction. Besides, the depth of the layer with compressive residual stress is about 60 μm in both directions.

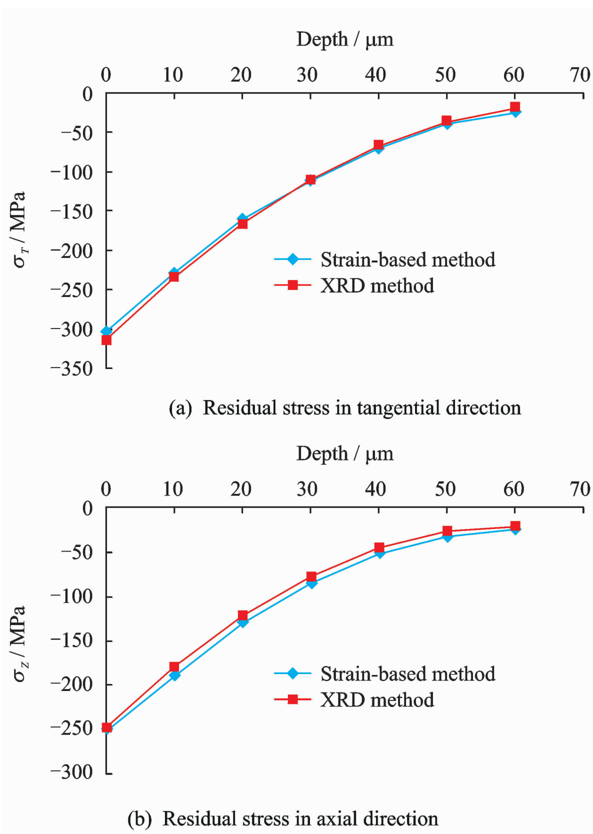


Fig. 5 Residual stress measured by two methods

The stress profiles along both the axial and the tangential directions obtained from the two methods agree well with each other. The maximum error between the two results is less than 10 MPa, which can be ascribed to the limit of the measuring equipment. The margin of error from this method is no more than ±10 MPa, which can be accepted in most cases. By analyzing the obtained results, it can be concluded that the accuracy of the strain-based method proposed in this paper is high enough and it can be used to measure the residual stresses in the internal surface of the tube in practice.

6 Conclusions

A strain-based method is proposed to measure the residual stresses induced by boring in internal surface of the tube, and it is based on the strains on external surface of the tube. The results of the finite element analysis show that if the ratio of tube length to external diameter reaches no less than $\lambda = 50/45 = 1.11$, the accuracy will be high enough for both strain-based measuring method and the correction method proposed by Ref. [18]. The measurements obtained from strain-based method are compared with those obtained from XRD method. Both the stress profiles correspond to each other very well and the validity of the strain-based method has thus been confirmed. Therefore, the proposed method can provide stress profiles with high accuracy and can take the place of XRD method in practice in some cases with much cheaper equipments.

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