Measurement of Residual Stress in Metallic Materials Processed by Means of SMAT

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Summary SMAT (surface mechanical attrition treatment) is an effective solution to improve the mechanical property of metallic materials, in which residual stress is an important parameter for the control of SMAT processing. In order to measure the residual stress in the subsurface of SMATed materials, a method that combines ESPI (electronic speckle pattern interferometry) and blind hole-drilling method is presented in this paper. By drilling a blind-hole, the state of equilibrium in SMATed material is destroyed, and the surface deformation induced by stress relaxation is measured by ESPI. Since the relation between relieved strain field and corresponding residual stress can be accurately determined by finite element simulation, the relieved residual stress may be inversely calculated from the result measured by ESPI. A group of experiments of SMATed aluminium plate is given to demonstrate the validity of this method.

INTRODUCTION

SMAT (surface mechanical attrition treatment) can significantly improve the mechanical property of metallic materials by fabricating a nanostructured surface layer that is induced by plastic straining [1]. Hence, residual stress measurement is considerably beneficial to explain the mechanism of SMAT. Although there are various methods [2] for residual stress method, blind-hole drilling method [2-4], due to its great advantages of reliability and convenience, is most widely used for the measurement of residual stress gradient with depth. In this way, residual stress within the SMATed materials is calculated from the hole-drilling induced surface deformation, which is traditionally measured by use of Rosette strain gauge. However, strain gauges can only provide three strain components, and moreover, eccentric error introduced by imprecise definition of hole-center and time-consuming caused by attaching strain gauges closely to the specimen is inevitable. Thus, the optical methods, such as moiré interferometry, digital image correlation (DIC) and electronic/digital speckle pattern interferometry (ESPI/DSPI), were proposed to replace the role of strain gauges for strain measurement. These optical methods can provide a full-field strain field, require much less surface preparation and identify the center of hole accurately, and thus, enable the improvement of the measurement precision. In above optical methods, dual-axis ESPI is preferred due to its merit of high-accuracy over DIC method and needless of attached diffraction grating in moiré interferometry.
Although several algorithms [4] had been reported to estimate the residual stress from a huge mass of whole-field data, there is still room for improvement in these methods. To our knowledge, the existing methods have some limitations that the whole-field data is not fully used or it can only be used to solve the through-hole problem. Thus, in this paper, a new algorithm based on least-square is introduced to estimate residual stress. Using ESPI, the relieved displacement field with regard to x and y direction is respectively measured, and subsequently the radial strain field is calculated from strain filed in Cartesian coordinate. According to the relation between relieved strain and stress obtained by FEM simulation, residual stress gradient with depth is evaluated from the abundant whole-field data. A group of experiments of SMATed aluminum plate is given to demonstrate the validity of this method.

PRINCIPLE

According to the elastic theory, residual stress with the materials removed by hole-drilling can be expressed as a function of relieved strain as below:

$$\varepsilon_j(r,\theta) = \frac{1+v}{E}\sum_{k=1}^{j}\bar{a}_{jk}\left(\frac{\sigma_x+\sigma_y}{2}\right)_k + \frac{1}{E}\sum_{k=1}^{j}\bar{b}_{jk}\left(\frac{\sigma_x-\sigma_y}{2}\right)_k \cos 2\theta + \frac{1}{E}\sum_{k=1}^{j}\bar{b}_{jk}\left(\tau_{xy}\right)_k \sin 2\theta \tag{1}$$

where ε_j is the surface strain relief after completing the j^{th} step of hole drilling, $\bar{a}_{jk}$ and $\bar{b}_{jk}$ are the constant matrices determined by FEM simulation, E and v are Young's modulus and Poisson's ratio of test materials, respectively, $\left(\sigma_x,\sigma_y,\tau_{xy}\right)_j$ is the stress vector existed within the j^{th} layer [3]. By comparing the difference of laser speckle field induced by stress relaxation, the in-plane displacement field is measured by ESPI, and using numerical differentiation, the strain vector in Cartesian coordinate is obtained, and can be transferred into strain in the system of polar coordinates. Since ESPI provides a whole-field data, an over-determined equation is founded. In order to solve this equation, Eq. (1) is rewritten as below:

$$\varepsilon_j = A_j + B_j p_k + C_j q_k + D_j t_k \tag{2}$$

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where $p_k = (\sigma_x + \sigma_y)_j, q_k = (\sigma_x + \sigma_y)_j, t_k = (\tau_{xy})_j$, and A_j, B_j, C_j, D_j is calculated in each layer according to the position of data point. The best solution of stress vector $(\sigma_x, \sigma_y, \tau_{xy})_j$ can be obtained when the least square error of equation (2) reaches the minimum.

EXPERIMENTAL RESULT AND DISCUSSION

In order to verify the proposed method, a group of specimens is prepared which is cut from a large plate of 2024 aluminum plate, and both sides were SMATed alternately. Figure 1 shows the relieved radial strain measured by ESPI after a hole of 0.5 mm depth is removed. Using proposed algorithm, compressive residual stress in the subsurface layer is estimated, which is showed in Fig. 2. As showed in Fig. 3, the precision of measurement result can be improved by using more strain data points. However, in this case, this effect is not significant when the number of points is over 60. Figure 4 shows the stress result of specimens treated in 1, 5, 15 minutes. Obviously, the treatment of 15-minutes produces much more compressive stress than the other two, which is agreed with the conclusion that the profile of stress is closely related to the coverage time.

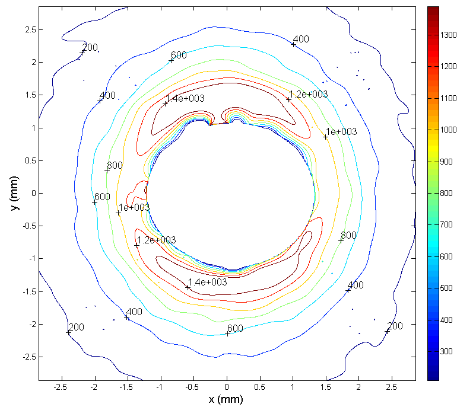

Fig 1. Radial strain field relieved by hole-drilling

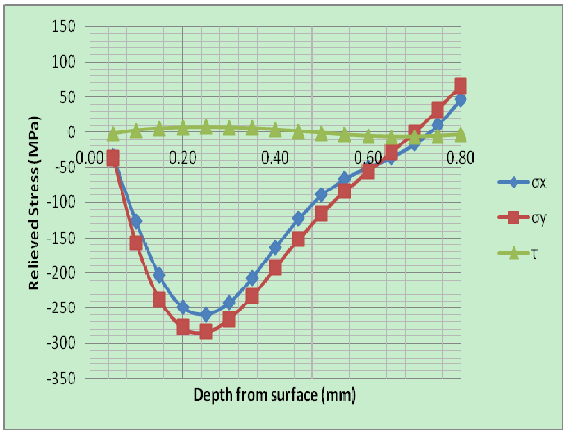

Fig 2. Stress calculated from relieved strain

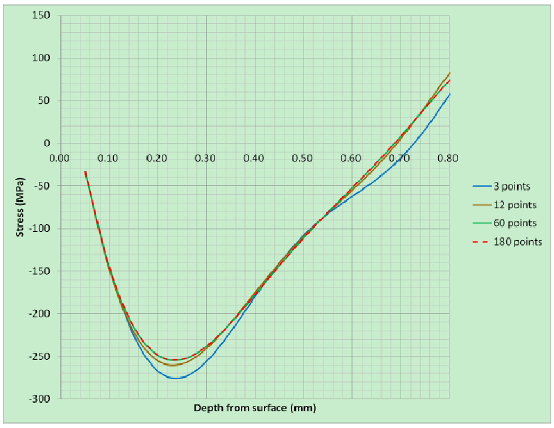

Fig 3. Stress estimated from different data points

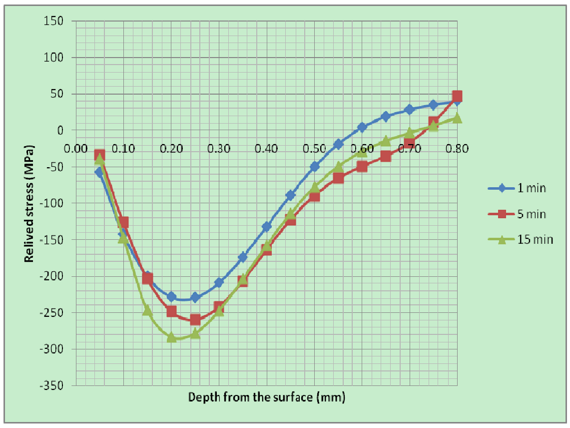

Fig 4. Comparison of stress induced by different treatment time

CONCLUSIONS

In summary, a method that combines ESPI and hole-drilling method is proposed to determine residual stress gradient with depth. As the least square method is used to calculate stress from the whole field strain data, the measuring accuracy is increased. This method has no special requirement for the material property, thus, it is also available for other materials, for example, metallic glass.

References

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