Measurement of Internal Residual Stress of the Laser Rapid Forming Parts by Incremental-step Hole Drilling Method

Youbin Lai\textsuperscript{1,2,a} Weijun Liu\textsuperscript{1,b} Yuhui Zhao\textsuperscript{1,c} Fuyu Wang\textsuperscript{1,2,d} Wenchao Han\textsuperscript{1,2,e}

\textsuperscript{1}Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang, China, 110016
\textsuperscript{2}University of Chinese Academy of Sciences, Beijing, China, 100039
\textsuperscript{a}yblai@sia.cn, \textsuperscript{b}wjliu@sia.cn, \textsuperscript{c}yhzao@sia.cn, \textsuperscript{d}wangfuyu@sia.cn, \textsuperscript{e}hanwenchao@sia.cn

Keywords: Laser rapid forming, Residual stress, Incremental hole drilling method, Calibration compensation coefficient

Abstract. In order to study the residual stress distribution in the titanium alloy laser rapid forming parts, the incremental-step hole drilling method is improved. Choose a calibration sample which has the same material as the test sample to conduct internal residual stress measurement by incremental-step hole drilling method. Conduct stress-release heat treatment (insulation 4 hours in 750 centigrade, furnace cooling) to the calibration sample before the measurement to uniform the internal stress. Calculate calibration compensation coefficient according to the calibration sample stress measurement result, and use the compensation coefficient to compensate the stress measurement result of the laser rapid forming sample. This method improves the reliability of internal residual stress measurement by incremental-step hole drilling method. Then use this method to measure the stress of laser rapid forming sample. The result shows that both the residual stress in the X direction and the Y direction is larger when the depth ranges from 1 mm to 3 mm. When the depth is greater than 3 mm, the residual stress decreases gradually with the hole depth increasing. The maximum value in the X direction is 147.13 MPa, and the maximum value in the Y direction is 236.32 MPa.

Introduction

Titanium alloy is more and more widely used in aviation equipment, because it has a series of advantages such as low density, high strength, corrosion resistance and so on. The traditional method of manufacturing large titanium alloy structure, overall forging for example, the process is long and complex, in addition, the requirement of the manufacturing technology and equipment is high, and the forming technology is difficult. It not only needs ton class heavy hydraulic forging industrial equipment, large-size forging billet machining and forging die manufacturing, but also needs large parts machining remove, long CNC machining time, low material utilization, long production cycle and high manufacturing cost [1]. Titanium alloy laser forming technology integrates the latest achievements in the field of mechanical engineering, CAD / CAM, CNC technology, laser technology and materials science. It can quickly transform design idea into a prototype with a certain structure and function or manufacture parts directly, reducing the processing costs significantly [2]. Metal laser forming technology takes a high-energy laser beam as a moving heat source. On one hand, the laser rapid heating and cooling provides extreme non-equilibrium conditions which can not be achieved by conventional means for material processing, making forming pieces have small, densification tissue and excellent overall performance, on the other hand, the uneven temperature field caused by the local heat input would inevitably lead to local heating effect, leading to weld pool solidification and cooling process inconsistent, resulting in the residual stress and deformation in the formed parts. The residual stress has very negative impact on the parts performance, the stability of the structure size and the forming precision. It will directly lead to the crack defects severely [3]. Therefore, the metal laser forming parts internal residual stress distribution characteristics study has important practical significance on the metal laser forming technology and the comprehensive quality of the formed parts improvement.
Theory and Method
At present, there are a lot of residual stress measurement methods [4]. According to the test method with or without destruction on test pieces, it can be divided into two categories, the physical non-destructive testing method and mechanical detrimental testing method. The non-destructive testing method includes X-ray diffraction method, magnetic method, ultrasonic method, neutron diffraction method etc.. The mechanical testing method includes split-full-release method, layer-by-layer cutting method, electrochemical corrosion delamination method, drilling method and moire interferometry method and holographic interferometry method based on drilling method etc.. The most mature method is drilling method and X-ray diffraction method. The test uses the incremental-step hole drilling method based on drilling method to measure residual stress of the titanium alloy specimen formed by laser forming technology. The basic idea of the incremental-step hole drilling method is as follows [5, 6]. If the parts interior exist the residual stress field and the elastic strain field, drill a small hole gradually in the stress field arbitrary node. If the feed amount is h each time, the residual stress here will be released, and the original stress field will be out of balance. At this time, there will produce a certain amount of release around the blind hole, making the original stress field reach a new equilibrium, forming a new stress and strain fields. Deepen the drilling depth, and the residual stress on the depth is gradually released. Measure the surface strain after each release. Since the hole is gradually drilled, as the approximation process, it is assumed that each time the feed amount h on the residual stress is uniform. Measure the surface strain $\varepsilon_n'$ after the release each time. Use the Eq. 1, Eq. 2 and Eq. 3 to obtain the test points main stress in the corresponding feed depth.

$$\sigma_{1nn} = \frac{\varepsilon^1_n + \varepsilon^3_n}{4A_{nn}} + \frac{\varepsilon^1_n - \varepsilon^3_n}{4B_{nn}} \cos 2\beta_n,$$

$$\sigma_{2nn} = \frac{\varepsilon^1_n + \varepsilon^3_n}{4A_{nn}} - \frac{\varepsilon^1_n - \varepsilon^3_n}{4B_{nn}} \cos 2\beta_n,$$

$$\tan 2\beta_n = \frac{\varepsilon^1_n - 2\varepsilon^2_n + \varepsilon^3_n}{\varepsilon^1_n - \varepsilon^3_n},$$

where $\sigma_{1nn}$ and $\sigma_{2nn}$ is the main stress of the $n$th feed depth layer, $\beta_n$ is the angle of the maximum principal stress and the x-axis, $A_{nn}$ and $B_{nn}$ is the relaxation coefficient of the nth feed layer, determined by the Eq. 4 and Eq. 5, $\varepsilon^1_n$, $\varepsilon^2_n$ and $\varepsilon^3_n$ is the test value of the strain gage determined by Eq. 6.

$$A_{nn} = -\frac{1 + \mu}{2E} \frac{R^2}{l_1 l_2},$$

$$B_{nn} = -\frac{1}{E} \frac{2R^2}{l_1 l_2} \left[ \frac{1 + \mu}{4} \frac{R^2 (l_1^2 + l_1 l_2 + l_2^2)}{l_1 l_2} \right],$$

$$\varepsilon_{n}^j = \varepsilon_{nn}^j - \sum_{i=1}^{i=n-1} \varepsilon_{in}^j \quad j = 1, 2, 3.$$

where R is the radius of the drilled hole, $l_1$ and $l_2$ is the distance between the strain gauge at both ends and the center of the hole respectively (Fig. 1), $E$ is the elastic modulus of the titanium alloy, $\mu$ is the titanium alloy Poisson ratio, $\varepsilon_{nn}^j$ is the total strain of the surface strain gage, $\varepsilon_{in}^j$ is the strain caused
by the release of the $i$th time feed depth layer. Thus, it can be calculated the residual stress in X direction and Y direction of the $n$th feed depth layer by the Eq. 7 and Eq. 8.

$$\sigma_{xxn} = \frac{\sigma_{1nn} + \sigma_{2nn}}{2} + \frac{\sigma_{1nn} - \sigma_{2nn}}{2} \cos 2\beta_n,$$

(7)

$$\sigma_{yy} = \frac{\sigma_{1nn} + \sigma_{2nn}}{2} + \frac{\sigma_{1nn} - \sigma_{2nn}}{2} \cos 2\beta_n.$$

(8)

Incremental-step hole drilling method has a very critical issue. It uses the surface strain gauge to collect the strain release value of every layer. With the hole depth increasing, the surface strain gauge measurement accuracy will be affected. For this reason, use the method of measuring and calibrating the sample pieces internal residual stress to fit the compensation coefficient, and then the test measurement results shall be compensated. Specifically, select a calibration sample which is the same material as the molding sample, conduct stress-release heat treatment (insulation 4 hours in 750 centigrade, furnace cooling) to the calibration sample before the measurement to uniform the internal stress. In the surface of the calibration sample, take three measurement points which are shown in Fig. 2. Measure the internal residual stress by incremental-step hole drilling method, drilling a total of five layers, each layer having a thickness of 1mm. The measurement results are shown in Table 1. The internal residual stress of the calibration sample after the stress-release heat treatment should be uniform. But it can be seen from Table 1, the stress value measured by incremental-step hole drilling method is not uniform. It demonstrates that compensation for the method is very necessary.

![Fig. 1 Diagram of strain gauge](image1)

![Fig. 2 Diagram of calibration sample measurement points distribution](image2)

### Table 1 Calibration sample residual stress measurement results

| Depth [mm] | Measurement point 1 | Measurement point 2 | Measurement point 3 |
|------------|---------------------|---------------------|---------------------|
|            | $\sigma_x$ [MPa]   | $\sigma_y$ [MPa]   | $\sigma_x$ [MPa]   | $\sigma_y$ [MPa]   | $\sigma_x$ [MPa] | $\sigma_y$ [MPa] |
| 1          | 15.8                | 15.4                | 36.1                | 33.1                | 28.8              | 32.3              |
| 2          | 19.2                | 20                  | 25                  | 26.9                | 28.1              | 28.5              |
| 3          | 1.9                 | 3.8                 | -2.3                | 0.1                 | -0.4              | 3.9               |
| 4          | 1.9                 | 2.7                 | -0.8                | -0.4                | 1.9               | 7.3               |
| 5          | 10                  | 15.4                | 15.4                | 18.1                | 9.6               | 13.5              |

To improve the compensation accuracy, take the average of the three points measured value as a reference to compensate the result. The first layer (depth 1 mm) is the closest to the strain gauge, thus the measured value is considered accurate. Take the measured value of the first layer as compensation benchmarks. Calculate the compensation coefficient of the second layer (depth 2 mm), the third layer (depth 3 mm), the fourth layer (depth 4 mm) and the fifth layer (depth 5 mm) with respect to the first layer.
\[ \mu_{12x} = 0.1, \mu_{13x} = 1, \mu_{14x} = 0.96, \mu_{15x} = 0.57. \]  
\[ \mu_{12y} = 0.06, \mu_{13y} = 0.9, \mu_{14y} = 0.88, \mu_{15y} = 0.42. \]

where \( \mu_{1i} \) is the X-direction stress compensation coefficient of the \( i \) th (\( i = 2, 3, 4, 5 \)) layer with respect to the first layer, \( \mu_{1j} \) is the Y-direction stress compensation coefficient of the \( j \) th (\( j = 2, 3, 4, 5 \)) layer with respect to the first layer.

**Experiments**

The experiment is conducted on 5 KW CO\(_2\) cross flow laser device, and the measurement sample is prepared in a vacuum environment. The forming powder and the substrate material is both titanium alloy. Polish the substrate before the experiment to remove the surface oxide scale layer and increase its surface finish, and then wash it with acetone. The titanium alloy powder is placed at 120 centigrade vacuum environment for drying treatment. The specific process parameters are shown in Table 2. The prepared sample piece size is 56 mm\( \times \) 24 mm\( \times \) 30 mm. The sample forming process and the forming parts after pretreatment are shown in Fig. 3 and Fig. 4.

| Table 2 The main process parameters of laser rapid forming |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Laser power [W] | Scanning speed [mm s\(^{-1}\)] | Powder feeding rate [g min\(^{-1}\)] | Scanning pattern |
|----------------|-------------------------------|-------------------------------|------------------|
| 3500           | 7                             | 0.7                           | Intersect scanning |

![Fig. 3 Sample forming process](image1.png) ![Fig. 4 Forming parts after pretreatment](image2.png)

The resistance strain gauge paste technology is very complex. The paste quality plays an important role in the measurement reliability, and is therefore a very crucial part [7]. The experiment is according to the following steps strictly. Design strain gauge distribution program. The strain gauge distribution in experiment is consistent with the strain gauge distribution in calibration sample (shown in Fig. 2). The diameter of the drilled hole is 1.5 mm, and the interval between the strain gauges is 18 mm to avoid the interference. Select strain gauge. Firstly, check the appearance of the strain gauge, and get rid of the strain gauge with the sensitive gate having shape defect, and the strain gauge with bubble, mildew, rust spots. Measure the resistance of strain gauge by avometer. Polish the surface of the sample to make it smooth and flat. Draw cross lines with the needle precisely in the measured point for easy positioning. Clean the parts of the surface to be tested with a cotton soaked with acetone. Clear away grease dirt and keep it clean. Coat a layer of adhesive on the back of the selected strain gauge evenly, then align the cross lines of the strain gauge to the cross lines of the sample under test. Correct the direction gently, and then cover it with a piece of cellophane. Roll the strain gauge in one direction with a finger to extrude the bubble and the excess glue. Ensure the adhesive layer is as thin and uniform as possible, and then use the same adhesive to paste the lead terminals (shown in Fig. 5). Dry for 4 hours or more naturally. Check the insulation of the strain gauge resistors and the strain gauge lead by avometer. Weld the two lead wires of the strain gauge on the lead terminals (shown in Fig. 6). Measure the internal residual stress by incremental-step hole drilling method. When drilling the hole, use a dedicated alignment means for alignment through the microscope, and then drill the hole uniformly (Fig. 7) to the set depth. There are five layers, and each layer has a thickness of 1 mm.
Experimental Analysis

Use incremental-step hole drilling method to measure the stress of molded sample, and use the compensation coefficient mentioned before to compensate the measurement result. The result is shown in Table 3.

Table 3 Residual stress

| Depth [mm] | Measurement point 1 |  | Measurement point 2 |  | Measurement point 3 |  |
|------------|---------------------|---|---------------------|---|---------------------|---|
|            | $\sigma_x$ [MPa]   | $\sigma_y$ [MPa] | $\sigma_x$ [MPa]   | $\sigma_y$ [MPa] | $\sigma_x$ [MPa]   | $\sigma_y$ [MPa] |
| 1          | 103.24              | 177.04               | 135.08              | 236.32               | 147.13              | 197.75               |
| 2          | 101.42              | 159.26               | 134.3               | 211.42               | 146.63              | 176.7                |
| 3          | 99.77               | 161.66               | 132.77              | 213.85               | 150.58              | 183.75               |
| 4          | 80.98               | 114.13               | 91.99               | 111.94               | 106.29              | 105.48               |
| 5          | 55.37               | 70.88                | 68.79               | 101.92               | 99.28               | 104.93               |

Analysis the residual stress in the X direction variation of each measurement point with depth change (Fig. 8). It can be seen that the residual stress of each measurement point is tensile stress. The stress value is larger in the depth range of 1~3 mm. The maximum value is 147.13 MPa. When the depth is more than 3 mm, with the hole depth increasing, the residual stress decreases gradually and has the trend of evolving to the compressive stress. Analysis the residual stress in the Y direction variation of each measurement point with depth change (Fig. 9). It can be seen that the residual stress of each measurement point is tensile stress. The stress value is larger in the depth range of 1~3 mm. The maximum value is 236.32 MPa. When the depth is more than 3 mm, with the hole depth increasing, the residual stress decreases gradually and has the trend of evolving to the compressive stress.

Fig. 8 The residual stress in the X direction variation of each measurement point with depth

Fig. 9 The residual stress in the Y direction variation of each measurement point with depth

Fig. 10 shows the change of the residual stress in the X direction for each depth with the site change. It can be seen that at the same depth, the residual stress in the X direction of the second measurement point (sample internal position) is substantially the mean value of the first measurement point (sample...
edge position) and the third measurement point (sample edge position). Fig. 11 shows the change of the residual stress in the Y direction for each depth with the site change. It can be seen that at the same depth, the residual stress in the Y direction of the second measurement point (sample internal position) is greater than the first measurement point (sample edge position) and the third measurement point (sample edge position).

Fig. 10 The change of the residual stress in the X direction for each depth with the site change

Fig. 11 The change of the residual stress in the Y direction for each depth with the site change

Conclusion

The incremental-step hole drilling method can measure the residual stress of different depth. But it needs to be compensated calibration in order to get more reliable result. The residual stress of each measurement point is larger in a depth range of 1~3 mm. When the depth is more than 3 mm, with the hole depth increasing, the residual stress decreases gradually. The residual stress in the X direction of the sample internal is approximate to the mean value of the sample edge’s. The residual stress in the Y direction of the sample internal is greater than the sample edge’s.

References

[1] H.M. Wang, S.Q. Zhang, X.M Wang: Chinese Journal of Lasers, Vol. 36(2009) No.5, pp.3204-3209.
[2] S. Yang, M.L. Zhong, Q.M. Zhang: Laser Technology, Vol. 25(2001) No.4, pp. 254-257.
[3] J. Yang, W.D. Huang, J. Chen, X. Lin: Applied Laser, Vol. 24(2004) No.1, pp. 5-8.
[4] M. Steinzig, T. Takahashi: Experimental Techniques, Vol. 27(2003) No.6, pp.59-63.
[5] Y. Kong, W.J. Liu, Y.C. Wang, H.Y. Bian, Y.H. Zhao: Chinese Journal of Mechanical Engineering, Vol. 47(2011), No.24, pp.74-82.
[6] Y.Q. Xu, J.F. Li, Z.L. Wang: Journal of Northwestern Polytechnical University, Vol. 27(2009), No.1, pp. 39-42.
[7] W. Dong: Shanxi Architecture, 2011, 37(28): 46-48.