Measurement of the Residual Stress in the Micro Milled Thin-Walled Structures

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Abstract. A new microbridge testing method to measure the residual stress of the micro milled thin-walled structure is proposed. Since this type of microbridge structures is of micron dimension, the normal residual stress testing methods, such as XRD and hole-drilling method, are difficult to be applied. To solve this problem, theoretic analysis is firstly conducted to provide a formula of deflection vs load, considering the existence of the residual stress in the micro structure. Using this formula, the residual stress can be evaluated. The 3J21 Alloy sample is prepared via the micro milling process. Experimental result shows that the residual stress in micro structure is around 120MPa, with the cutting depth of 10 μm and feed rate of 1mm/s.

1. Introduction

Thin-walled micro structures made of elastic alloy are widely used in the inertial components, such as accelerators and gyroscopes. In these applications, the residual stress is strictly restricted, as well as high shape accuracy is required. The conventional MEMS related manufacturing technologies, such as silicon processing technologies, LIGA, high energy beam machining and micro EDM machining technology, can’t meet the machining requirements for this kind of precise micro structure. High speed micro milling provides a good solution to this problem, it can generate the structure with high shape accuracy. However, just as other mechanical machining methods, residual stress can hardly be completely avoided during the micro milling. Therefore, to measure and predict the residual stress in the micro milling process is important for the quality control of the thin-walled micro structures.

At present, many methods have been developed to measure the residual stress in the finished parts, such as hole-drilling method, XRD and so on. Since the dimension of the micro structure is at about 100 μm, it’s difficult to apply these existing methods to measure the residual stress in the micro structure. Till this point, few research work on the investigation of the residual stress in the micro milled structures has been reported. Therefore, new method must be considered.

In this paper, a microbridge testing method based on the nano indentor is presented. According to the elastic-plastic theory, when the loading and unloading curves of the micro structure have been determined, the Yang’s modulus and the residual stress of the micro structure can be calculated. The advantages of this method include, first, not only residual stress can be measure, some other mechanical properties can also be measured at the same time. Second, this method is suitable for the measurement of the micro mechanical properties. Its loading force can be controlled at nano Newton level, so it can still be considered as a kind of non-destructuring method. This new method was firstly
developed by Zhang [1-3]. Even though Zhang’s work mainly focused on the thin film of Nitride Silicon deposited on the Si substrate via CVD method, the effectiveness of the microbridge testing methods has been proved [1-5].

2. Micro Milled Thin-walled Structure
A micro milling machine is used to fabricate the thin-walled structure. This machine uses the piezo ultrasonic linear motor to drive the slide stable directly, as shown in Figure 1. Linear optical encoder with a resolution of 10nm is used to close the control loop. Positioning accuracy of this machine is ±0.2μm. High speed air turbine driven spindle is utilized to generate high cutting speed, and its maximum speed is 160,000RPM and its radial and axial runout is less than 1μm.

As illustrated in Figure 2, a thin-walled micro structure is machined, its length, width and thickness are 150μm,150μm and 8μm respectively. The material of this part is 3J21 alloy.

3. Modelling
Nano indentor is used to apply load on the micro bridge as shown in Figure 2, its corresponding deflection can be measured and recorded at the same time. Therefore, the force-deflection curve is gotten. According to the elastic-plastic theory, the residual stress generated during the micro machining process can be calculated. Figure 3 is the schematic depiction of this micro bridge test.

\[ w = \frac{Q \tanh(\frac{kL}{2})}{2N_1k} + \frac{Ql}{4N_0} - \frac{M_0}{N_1} \left( \frac{1}{\cosh(\frac{kL}{2})} - 1 \right) \]  

In the case of small deflection, the bridge deflection at the bridge center where the lateral load is applied can be expressed as follows,
\[ M_0 = \frac{l}{\cosh(\frac{kl}{2})} \cdot \frac{1}{2ktanh(\frac{kl}{2})} Q \] (2)

Where, 
\[ k = \sqrt{\frac{N_r}{D}}, \quad D = \frac{E_f t^3}{12}, \quad M_0 \] is the connecting force between the bridge and the body material, 
\( l \) and \( t \) are the length and the thickness of the bridge, \( Q \) is the load, \( w \) is the deflection, \( E_f \) is the modulus and \( N_r \) is the residual force per unit width along the length direction. As illustrated in Figure 3, the micro bridge can be considered as built-in end, then Eq(1) and Eq(2) can be simplified as Eq(3),

\[ w = \left[ \frac{k}{4} \cdot \tanh\left(\frac{k}{4}\right) \right] \frac{Q}{N_r, k} \] (3)

To evaluate the residual stress, the experimental load-deflection curve is fitted to the theoretical solution via least square technology, i.e. minimizing the positive function,

\[ S = \sum_{i=1}^{n} \left[ w_i^e(Q) - w_i^t(Q, N_r, E_f) \right]^2 \] (4)

Where \( n \) is the number of data, \( W_i^e \) is the experimentally observed deflection, \( W_i^t \) is the theoretical solution of Eq(1) – Eq(3).

4. Experimental Analysis

To get the load-deflection curve, a MTS nano indenter with microwedge probe is utilized. This experimental setup is illustrated in Figure 4. Since the small deflection model is used, the displacement of the microbridge is restricted in 3\( \mu \)m, less than half of the thickness. The loading and unloading procedure is repeated for 3 times, and then the curve in Figure 5 is got. At the same time, the modulus of the microbridge structure was also measured, see Figure 6. Taking the surface roughness and the plastic deformation into consideration, the value at the displacement of 800nm was considered as the actual modulus. In this case, the measured modulus \( E_f \) is about 200GPa.

Then, using Eq(1)-(4), the residual stress \( \sigma_r = \frac{N_r}{t} \) can be derived. The final result is around 120MPa.

5. Conclusion

With the microbridge testing method, the residual stress in the micromilled microbridge type structures has been evaluated. This is only the first step in the long run to study on the mechanical properties of the micro milled parts or structures. For the future work, the residual stress variation under different cutting depth, different feed rate and different spindle speed need to be studied, then it

![Figure 5. Load-displacement.](Image)

![Figure 6. Modulus.](Image)
would be possible to predict the residual stress before the micro machining process and this may be a good reference to the design of the micro parts or structures.

**References**

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