Distribution and Optimization of Residual Stress in Ultrasonic Rolling

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Abstract. The appropriate residual compressive stress can effectively improve the fatigue strength of parts and prolong the service life of the parts for aerospace aluminum alloy components. In this paper, the surface residual stress of 7050 aluminum alloy by ultrasonic rolling was investigated, the principle of ultrasonic rolling was analyzed, it was found that ultrasonic rolling can effectively improve the surface residual compressive stress by comparing the distribution of residual stress on the surface after milling and ultrasonic rolling. Finally, the parameter optimization of the residual stress control was acquired, the better surface strengthening layer by combining the high frequency and high pressure parameters under the premise of ensuring the surface roughness could be obtained.

1. Introduction

Ultrasonic rolling is a new technology of surface treatment technology, which is achieved by combining high frequency vibration with traditional rolling processing. The principle is shown in Fig. 1. The main motion of the rolling head is ultrasonic vibration and accompanied with free rolling, which aims to reduce the friction between the rolling head and the metal parts. In the processing, the rolling head performs high-speed impact on the surface of the metal parts, which leads to violent plastic deformation of the surface and the sub-surface layer. The "valleys" are filled with "peaks" at the surface of the metal parts, which results in reduction in the surface roughness, and the distribution of residual compressive stress on the surface of the metal parts is formed[1]. Finally, the mechanical properties of the metal part effectively improve due to the formation of surface strengthening layer.

Fig. 1 Ultrasonic rolling principle

At present, it is insufficient to strengthen the surface of the metal parts and improve the fatigue life by means of the traditional surface hardening techniques such as shot peening, rolling, extruding, and improving the constrained layer materials [2-4], the surface quality after ultrasonic rolling is especially better than the traditional surface hardening technology [5], it has gradually attracted increasing interests in the surface strengthening.
To date, many scholars had reported that the surface residual stress and strengthening of ultrasonic rolling various materials. Sun Xin et al [6] conducted contrast test of ultrasonic rolling intensifying on A100 steel and found that residual stress after ultrasonic rolling strengthening increased by 70%. Zhang Caizhen et al [7] studied the residual stress field of aeroengine titanium alloy blades, it was reported that there was a large residual stress and uniform distribution on the surface after shot peening. Ismail et al [8] established a three-dimensional finite element model of the rolling process and analysed the distribution of the equivalent residual stress on the surface after multiple rolling. Ye Han et al [9] carried out ultrasonic rolling strengthening treatment for 7050 aluminum alloys after finish turning, it was discovered that ultrasonic rolling can introduce a certain depth of residual compressive stress by contrasting the samples before and after the strengthening treatment.

Some studies had shown that the performance of parts improvement after ultrasonic rolling parts surface mainly in: Ultrasonic machining produces work hardening effects that lead to the wear resistance of the parts were effectively improved; for another, the fatigue resistance and corrosion resistance of the parts was guaranteed under the formation of a stable residual compressive stress layer [10-13]. In the paper, the study for aerospace aluminum alloy 7050 by ultrasonic surface rolling of strengthening was done, it also provided useful guidance to theoretical basis for the control and optimization about the distribution of the ultrasonic rolling surface residual stress.

2. Material and methods

2.1. Experimental Material
The material was aluminum alloy 7050 with chemical composition (mass, %) of 0.04 Cr, 5.7-6.7 Zn, 0.15 Fe, 1.9-2.6 Mg, 2.0-2.6 Cu, etc, its tensile strength was 524MPa and yield strength was 469MPa.

2.2. Experimental methods
The objective of the present work was to investigate the influence of ultrasonic static pressure parameters on ultrasonic rolling, the single-factor method was employed for ultrasonic processing experiments. The experimental parameters were shown in Table 1.

| Parameter | Static pressure(N) | Amplitude(um) | Current(A) | Frequency(kHz) |
|-----------|-------------------|---------------|------------|----------------|
| Value     | 800/1000/1200/1400/1600 | 6             | 1          | 30             |

Ultrasonic rolling three-way forces experiment was conducted to investigate the variation on the roll pressure in the ultrasonic strengthening process by changing the static pressure. The experiment was performed on a CNC vertical machining center. The triaxial force was measured in the kissler 9257b dynamometer. The test site was shown in Fig. 2.

![Fig. 2 The photo of the three-axis force measurement](image)

2.3. Measurement Method
In this paper, the blind hole method which was based on stress release theory was employed to measure the residual stress, the principle is shown in Fig. 3. The maximum and minimum principal stresses was σ1 and σ2, R1, R2, R3 were strain gauge, respectively. The strain gauge was attached at the test point, then drilled a certain depth of hole on the measuring point, when the local stress to be
delivered, the drill hole would produce a slight strain. Then, residual stress was calculated by the change of the strain gauge resistance. Strain gauge and drilling position were exhibited in Fig. 4.

![Fig. 3 Schematic diagram of blind hole residual stress measurement](image)

![Fig. 4 The photo of strain gauge and drilling position](image)

In the practical measurement, the blind hole diameter was 1mm. According to the experience, the drilling depth was generally 2 times of the hole diameter. Thus, aimed to achieve the complete release of stress the depth of the blind hole was taken as 3mm in this experiment, and aimed to completely release, the depth of each drilling was 0.5mm.

3. Results and discussion

3.1. Analysis of ultrasonic rolling mechanism

![Fig. 5 Grain refinement process in plastic deformation zone and surface microstructure after ultrasonic rolling](image)

Ultrasonic rolling was an additional ultrasonic vibration on the basis of traditional rolling, so that the surface of the metal parts was simultaneously subjected to the dynamic pressure caused by the impact source and the static pressure, the force generated by the combination of the two forces caused the elastoplastic deformation on the surface of the metal parts, which resulted in surface easier to formed deeper hardened layer, greater residual compressive stress, and better surface quality. Meanwhile, the violent and uniform plastic deformation of the metal surface will inevitably result in serious smashing and thinning on the grains in the original state at a certain depth of the metal parts under the joint action of static pressure and dynamic pressure. The reciprocating processing led to the surface of the metal parts uniformly stressed, the deformation and the deformation of depth were increased, resulted in the grains further refined. The process was presented in Figure 5(a)-(e), which can bring about the surface of the grain refinement to form ultra-fine crystals even to nanocrystals. It was realized that the strength and hardness of the material to several times that of the matrix coarse-grained material in the condition of without changing the composition of the material. Fig. 5(f) shows microscopic inspection of aluminum alloy 7050 after ultrasonic rolling, it was reported that a layer deteriorating from processing of the matrix material was formed in the cutting surface layer, and crystal grains in the layer were significantly refined, which coincided with the refined grains in Fig. 5(e).

3.2. Comparison of residual stress between principle milling and ultrasonic rolling

According to the three-way strain value \( \varepsilon_1, \varepsilon_2, \varepsilon_3 \) obtained from residual stress detection, and the calculated residual stress values \( \sigma_1 \) and \( \sigma_2 \), it can be seen that the residual stress values in the two main directions didn’t continue to grow after the drilling depth reached 2mm, thus, it can be determined that the stress has been released substantially completely at the position of 3mm. Table 2 summarizes the data from the 7050 drilled hole at 2mm. The signs of the strain values \( \varepsilon_1, \varepsilon_2, \varepsilon_3 \) and the principal stress...
direction angle "θ" represent the direction, and the residual stress value $σ_1$ and $σ_2$ represent the nature of the residual stress value, where ‘+’ represents the residual tensile stress and ‘-’ represents the residual compressive stress, respectively.

Table 2. Surface Residual Stress Value of Aluminum Alloy 7050

| Factor No. | pressure(N) | $ε_1/μm$ | $ε_2/μm$ | $ε_3/μm$ | $σ_1/MPa$ | $σ_2/MPa$ | $θ$  |
|-----------|------------|---------|---------|---------|----------|----------|-----|
| 0         | 0          | 8.01    | 18.86   | 0.72    | 10.6     | -6.49    | -7.94|
| 1         | 600        | 67.72   | 71.06   | 76.22   | -47.40   | -49.46   | -6.02|
| 2         | 8000       | 75.66   | 90.56   | 100.07  | -70.20   | -75.41   | 10.62|
| 3         | 1000       | 95.38   | 113.11  | 116.89  | -85.37   | -92.47   | 16.48|
| 4         | 1200       | 98.43   | 118.25  | 120.63  | -119.05  | -130.02  | 20.56|
| 5         | 1400       | 102.64  | 128.33  | 122.70  | -35.39   | -140.25  | 28.68|

In Table 2, No. 0 shows the residual stress value of the untreated surface of the metal parts, as apparent from Table 2, there was mainly residual tensile stress on the untreated surface, the reason mainly in: the serial No.0 was rough milled and it was measured the milled surface, in the process of milling, the tool surface was attributed to the removal material processing, and the surface of layer metal was finally broken by stretching. The tool removal played a major role when the cutting depth was small that caused the surface to produced tensile residual stress. It can be easily observed that No. 1-5 in Table 2, the residual stress which generated on the surface after ultrasonic rolling was residual compressive stress which along with the pressure increased, it showed that the ultrasonic rolling had significant effect on improving the residual compressive stress of surface of the metal parts. It was obvious that the residual compressive stress reached maximum of 135.39MPa under the pressure of 1400N.

3.3. Comparison of surface residual stress

3.3.1. Analysis of the residual stress at different depths of cutting

Fig. 6 Different depth of cutting: (a) 0.2mm ; (b) 0.6mm ; (c) 1mm; (d) 1.4mm; (e) 1.8mm; (f) positioning hole

Fig. 7 Effect of depth on cutting force

Fig. 8 Residual stress at different depth

Fig. 6 shows the metal parts after different depths of cutting. Fig.7 presents the effect of depth of cut on cutting force. Fig. 8 reveals the residual stress at different depths of cut. It was cleared that with bigger depth of cutting comes bigger cutting force from Fig. 7. For Fig. 8 shows that in pace with the depth of cutting increased, the residual stress transformed from the residual tensile stress to the residual compressive stress, the reason was that the cutting force increases with the depth of cut increased, the plastic deformation of metal was further increased, plastic deformation was an important cause of residual stress, it can be perceived from Fig. 8 that the increased in plastic deformation caused the residual stress to transform from residual tensile stress to residual compressive stress when the depth of cutting was sufficiently large. Although the residual compressive stress was beneficial to the fatigue strength of the part, which can be created by raising the depth of cut, however, in terms of actual processing, shake of the body would be induced due to the excessive depth of cut that will conduce roughness of the machined surface not up to the required requirements. Thus, it was difficult to increase the depth of cutting to achieve a significant improvement in residual compressive stress.
3.3.2. Surface residual stress comparison analysis

The results indicated that the residual compressive stress can be generated by ultrasonic rolling and milling. But the residual stress distribution regular produced by the two processing methods was different. The results are shown in Fig. 9 by comparing the residual stress at different depths of cutting of the metal parts after ultrasonic rolling and milling.

![Fig. 9 The distribution regular of residual stress layer depth](image)

It can be educed that the metal parts after ultrasonic rolling produce a residual compressive stress in the depth of 3mm from Fig. 9. The maximum residual compressive stress was 2mm which the value was 145MPa. The residual compressive stress was directly proportional to the depth of the layer during 0-2mm, and the trend of 0.5-2mm was more obvious. It can be found that residual compressive stress has a tendency to decrease in 2-3mm, the surface refinement layer has a certain thickness based on the ultrasonic rolling mechanism, grains transition from refinement to matrix coarse crystals with the increase in thickness, led to the residual compressive stress gradually decreased. The metal parts after milling process had residual compressive stress of 0.5-2mm from the surface, and the maximum residual compressive stress was 10MPa. It was evident that ultrasonic rolling was the effective way to produce residual compressive stress.

3.4. Optimization of ultrasonic rolling process

Due to the process parameters of the ultrasonic rolling played an important role in the surface of the metal parts strengthening, the pressure changed abruptly in the actual processing and had immediate influence on the frequency. The ultrasonic rolling experiments were performed on the combined parameters under different pressures and frequencies, the experimental data were interpolated by Matlab. The results are shown in Fig.10.

![Fig. 10 Effect of pressure and frequency on surface residual compressive stress](image)

As can be seen from Fig. 10, the residual compressive stress generated was small when the pressure and the frequency was low, the reason lied in the combination of small frequency and pressure was similar to the traditional rolling principle, it can't be achieved the large surface residual compressive stress. The residual compressive stress was 101MPa when the frequency was 10KHz and the pressure was 1600N, the residual compressive stress was 55MPa when the pressure was 600N and the frequency was 40KHz. It was explicated that pressure and frequency had a significant effect on the formation of residual compressive stress. It can be obtained that the effect of pressure on residual compressive stress was more significant than frequency from the growth trend in Fig. 10. The residual compressive stress was 170Mpa when the frequency was 40KHz and the pressure was 1600N. As a result, combination of high frequency and high pressure parameters proved as an effective way to get a better surface enhancement layer and improve part performance.
4. Conclusions
In this paper, the 7050 aluminum alloy was subjected to ultrasonic rolling strengthening, it was found that the surface residual compressive stress after ultrasonic rolling was obviously higher than that of milling. It was discovered that the maximum residual compressive stress was at the depth of 2mm, and the maximum value was 145MPa in the analysis of the distribution of the residual stress along the depth of the layer, which had great effects on strengthening the metal parts. It was concluded that the effect of pressure on the formation of residual compressive stress was remarkable which was relative to the frequency by the studied of the experimental results. It was received that high pressure and high frequency were the best combination of processing parameters.

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