Research on Residual Stress Simulation on High Performance Aluminum Alloy Manufacturing

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Abstract. High-performance manufacturing is an integrated manufacturing of surface integrity and anti-fatigue surface strengthening to improve the service performance of key components. The stress concentration, fatigue failure and poor reliability cause by traditional processing have become technical bottlenecks restricting the development of industry. In order to research the influence of high performance manufacturing on the fatigue performance of workpieces, the residual stress distribution of 7050 aluminum alloy high performance manufacturing was studied by simulation. The stress layer on the surface of the workpiece was mainly tensile stress which was formed during cutting process, and it implied that the fatigue resistance of the workpiece was not effectively improved. The ultrasonic rolling strengthening treatment can effectively eliminate the residual tool marks and stress concentration. It was noted that stress layer of ultrasonic rolling was deeper than the cutting process, and the stress layer was mainly composed of residual compressive stress. The residual stress increased first and then decreased with the increased of depth, which can significantly improve the fatigue performance and service life of the workpiece.

1. Introduction

Due to its high strength, light weight, small size and high reliability, high-strength aluminum alloy is widely used in precision machinery main bodies and main bearing members in aviation, vehicles, ships and other fields [1, 2]. Fatigue failure is the main failure mode of high-strength alloy components, because the fatigue strength it’s sensitive to stress concentration and fatigue failure has low stress and no macroscopic deformation. Traditional forming process and special strengthening machining is hard to meet the requirement of the high performance of material surface integrity and fatigue resistance at the same time, which leads to the short life and poor reliability of the key components, thus restricting the development of manufacturing industry.

High-performance manufacturing is comprehensive manufacturing technology which aims to improve the serviceability of key components. Its core is the integrity of the material surface and the anti-fatigue surface strengthening. Based on the material performance characteristics of key components, it is urgent to develop high performance manufacturing technology with both shape (size, surface) and property (performance). Researches showed that the residual compressive stress played a decisive role in the fatigue performance, which can effectively counteracted the partial alternating load, hindered the
initiation and premature propagation of fatigue cracks, reduced the crack growth rate, and improved the fatigue performance of components [3]. For this reason, Luo [4] analyzed the residual stress in the gear manufacturing and found that the residual compressive stress formed on the gear surface can significantly improve the fatigue life of the gear. Edoardo Capello [5] founded the cutting effect on the surface residual stress of the workpiece. That was, the stress concentration and surface damage generated on the surface of the workpiece were not conducive to the fatigue performance of the workpiece. Meng [6] fully considered the influence of material anisotropy and high strain rate on dynamic mechanical properties, and constructed a material constitutive and fracture damage model suitable for cutting to achieve surface integrity forming. Although traditional forming and processing data was continuously optimized, machining marks, scratches, tissue damage, inclusions and other surface defects still caused surface stress concentration. In addition, a large residual tensile stress were formed on the surface of the workpiece, which can not meet the high performance requirements of key components. In order to achieve the goal of high-performance manufacturing, ultrasonic surface rolling technology was applied in manufacturing, it can not only enhance the integrity of the machined surface, but also remodeled the surface of the alloy component to eliminate the stress concentration and surface tensile stress caused by the discontinuity of the forming tool. Ultrasonic rolling can strengthen and modify the surface of workpiece after cutting. It was an ideal process for high performance manufacturing of aluminum alloy, thus breaking through the limitation of traditional “forming” manufacturing and developing a high performance manufacturing technology of “both shape and shape”.

The above studies showed that high-performance manufacturing had a significant effect on the fatigue performance and service life of the workpiece, but there was few study about the simulation of the process. This paper focused on the establishment of the cutting and ultrasonic rolling simulation model by using of finite element software Third Wave AdvantEdge and Abaqus software at first, and then finished the simulation of 7050 aluminum alloy cutting and ultrasonic rolling processing by presetting processing parameters. Finally, the residual stress of the material was analyzed and verified.

2. Finite element establishment

2.1. High-performance manufacturing process principle

![Figure 1. Processing principle.](image)

For the cutting process, the cutting surface forming principle of the material shown in (Figure 1a) which is realized by setting parameters such as cutting depth, feed rate and tool angle. And set up the processing parameters in the Third Wave AdvantEdge software. The grid was divided into software adaptive meshes. Since the cutting process had a certain resection of the surface of the material, in order to ensure the accuracy of the analysis of surface residual stress, the surface mesh of the material was refined. However, the stress concentration on the surface was hard to be avoided by optimization cutting the process parameters. The ultrasonic rolling (Figure 1b) was used to solve the problem. The processing principle of ultrasonic rolling was mainly by applying a certain amount of static pressure on the rolling head, and the vertical direction maintained between the rolling head and the workpiece, and ultrasonic
vibration of a certain frequency was applied in the vertical direction of the rolling head. In this way, the rolling effect of the ultrasonic machining and the longitudinal high-frequency impact were achieved. So, in order to study the phenomenon of ultrasonic rolling more quickly, ultrasonic rolling was completed by Abaqus/Explicit software for single rolling simulation. The size of geometric model was 25 mm×18 mm×10 mm, and the diameter of rolling head was Ф6 mm. The workpiece was meshed by an eight-node linear reduction integration unit (C3D8R), the sphere was set to a rigid body, and the uniform grid was used.

2.2. Material model

Based on the preliminary experiment of the research group, the modified J-C constitutive equation of aluminum alloy 7050 associated with the specific cutting conditions was obtained as follows [7].

$$\sigma = \left(463.4 + 319.5\varepsilon^{0.352}\right) \times \left[1 + 0.027 \ln(1 + \dot{\varepsilon}) \right] \left(1 - \frac{t - 25}{610}^{0.99}\right)$$

(1)

Where, $\varepsilon$ is the material strain, $\dot{\varepsilon}$ is the strain rate, $t$ is the test temperature. And use the value as shown in Table 1.

| Parameter | Elastic modulus E (GPa) | Density $\rho$ (kg/m³) | Poisson's ratio $\mu$ | Yield Strength (MPa) |
|-----------|-------------------------|-------------------------|----------------------|-----------------------|
| Value     | 70                      | 2810                    | 0.32                 | 463                   |

2.3. Boundary conditions and load application

The parameters of the cutting process is shown in Table 2. In the ultrasonic rolling stage, the bottom edge of the workpiece and the lateral side of the workpiece were fixedly restrained to prevent the error from increasing due to plastic deformation. The rolling ball needed to apply a vertical downward static pressure and vibration amplitude at the same time. The loading parameters are shown in Table 3.

| Project | Cutter material | Tool Front Angle $\gamma_0$ | Tool rear angle $\alpha_0$ | Feed speed $f_z$(mm/z) | Cutting depth $a_p$(mm) | Cutting speed $v$(m/min) |
|---------|-----------------|-----------------------------|---------------------------|------------------------|-------------------------|-------------------------|
| Value   | hard metal      | 10°                         | 6°                        | 0.1                    | 0.5                     | 3000–5000               |

| Static pressure (N) | 260 | 300 | 340 |
|---------------------|-----|-----|-----|
| Amplitude($\mu$m)   | 6   |     |     |
3.2. Residual stress distribution under ultrasonic rolling

Figure 3 is a cross-sectional view of the plastic deformation and stress distribution of the workpiece after ultrasonic rolling. It can be seen that the surface of the workpiece formed a strong plastic deformation layer after ultrasonic rolling. Since the ultrasonic rolling did not produce chips, strong plastic deformation caused the surface of the workpiece to be "peak clipping and valley filling". The surface structure of the workpiece becomes denser, forming a hardening phenomenon, and improving the surface hardness of the workpiece. The strong plastic deformation force also caused a significant plastic deformation height difference and residual stress layer on the surface of the workpiece. In order to analyze the distribution of residual stress, we performed fixed-point measurements on the residual stress along the depth direction. And the residual stress distribution curve (Figure. 4) was measured by changing the different static pressures. It can be seen that the residual stress on the surface of the workpiece was mainly compressive stress, and it tended to increase first and then decreased with the increased of depth. After ultrasonic rolling, the residual stress layer can reach a depth of about 1.5 mm, and the residual stress tended to increase first and then decrease. When it reached about 1.2 mm, the residual stress was close to zero. After that, the tensile stress also showed a trend of increasing first and then decreasing, and eventually stabilized. The experimental conclusions of the simulation was consistent with the experimental results of Zheng [9], which further validated the accuracy of the simulation.
3.3. Comparison and discussion

It was found that in the conventional forming process, the residual stress formed on the surface of the workpiece was mainly tensile stress, the stress layer was shallow, and the fatigue resistance of the workpiece was low. There was a certain gap with the high-performance manufacturing target, because the traditional processing method was easy to leave the surface of the workpiece with knife marks and stress concentration. It can be learned that the thick plastic deformation layer was formed on the surface of the workpiece after pressure and high-frequency vibration rolling, and the surface region was mainly composed of residual compressive stress. Since the residual compressive stress had a significant lifting effect against the fatigue, and can offset the impact and damage of the workpiece by the external alternating load, the service performance of the component was greatly improved. Ultrasonic rolling process had a certain remodeling effect on the surface of the workpiece, which enhanced the surface integrity of the material, and can also significantly eliminated the residual tool marks and stress concentration of traditional cutting and forming [10].

In short, the combination of traditional cutting and ultrasonic rolling played a crucial role in reducing the stress concentration on the surface of the workpiece and the initiation of micro-cracks, provided a realistic basis for the concept of high-performance manufacturing.

4. Conclusion

1) The traditional cutting process mainly consisted of residual tensile stress on the surface of the workpiece, and the stress layer was about 0.18mm, which was not conducive to the fatigue resistance and service performance of the workpiece surface.

2) The residual compressive stress formed by high-performance manufacturing on the surface of the material can effectively eliminate the hidden surface damage such as surface stress concentration. The residual compressive stress increased first and then decreased with the increase of depth, and reached equilibrium finally.

3) It can be seen that high-performance manufacturing can significantly increase the residual compressive stress on the surface of the workpiece, the surface integrity and fatigue resistance was improved effectively.

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