Deformation Control by VSR Technique on Al alloy Thin-Walled Components

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Abstract. Initial residual stress and machining stress of Al-alloy materials are the main factors that cause the deformation of Al-alloy thin-walled components. According to the theory of plastic yield and analysis of the stress-deformation characteristics in materials, the component is treated by using vibration stress relief (VSR) technology under three different aging of 30 min, 60 min and 90 min, after that the deformation are measured by coordinate machine respectively. The results of experiment present that, based on the balance of structural stress, after VSR aging 30 min, the component comes to deformation and becomes flatter than one before VSR. Similarly, as for complicated thin-walled component, the VSR aging time to achieve this effect mentioned above is about 90 min. The research manifests that VSR has a positive impact on deformation control of component even if structural stress level is extremely low in material.

1. Introduction

The large-scale aluminum structure components are widely used in aircraft manufacturing, such as frame, column, rib and wing. In the machining of slab, caused by the combined action of nonuniform field like milling force, fixture force, milling heat, macroscopical deformation happens in the structure components. Vibration stress relief (VSR) can change the residual stress by generating alternating stress in materials. At present, VSR is mainly used for ferrous metal. Stress concentration of the casting and welding parts can be significantly decreased and homogenized to satisfy performance requirements. Some meaningful results have been found by the researchers, such as improving the dimensional stability and reducing residual stress of bellows by aging [1], the stress release of welding parts by high frequency vibration [2, 3]. However, the research of the application of VSR in nonferrous metals is limited, because the residual stress is much small in nonferrous metals, it is very difficult for the material to yield by stress superposition. Shen et al. [4] studied the effects of process parameters of VSR for aluminum thick plate. Hu [5] studied stress release by VSR in different frequency and found the positive effects for stress homogenization of Al alloy thick plate. Cui, Teng and Lin [6] applied the ultrasonic method in aluminum welding components. The experiment results indicated the effects on the residual stress release. The VSR method can be applied to the surface characteristics of components to study its positive role in the material surface. In this paper, the micro mechanism is explained by dislocation theory.
2. Mechanism analysis

2.1. Stress distribution of the structure

The stress distribution of thin wall frame structures is very different with thick plates. Because of the milling process, the stress around thin walls is released. At the same time, high machining stress is generated on the machining surfaces. Generally, the stress on the bottom part will be strengthened due to the redistribution caused by the deformation. A stress area with high stress gradient generates on the machining surface. The initial stress is about ±20 MPa. However, the internal stress on the machining surface has reached 140 MPa just in the depth of 80 μm. This high stress gradient leads to the unstable internal energy in this area and needs to be released and homogenized. The section of the thin wall structure after machining is shown in figure 1, where the dark area is the machining stress area. Although VSR cannot significantly release the stress in the whole structure, in some stress concentration area, some positive effects can be observed by using VSR. Therefore, VSR can be applied to release the unstable internal energy caused by stress concentration in the machining stress area.

![Figure 1. Profile of component.](image)

2.2. Micro-mechanism analysis

In the view of dislocation, the micro yield condition, mechanism of the material and the relationship of aging, micro yield and stress homogenization can be analysed by combining dislocation motion and the change of microstructure. Dislocation can be seen as a line defect in materials. Amounts of dislocation pinning aggregation can be observed around grain boundary area in deformation. Therefore, in the high elastic energy area in the machining layer, the dislocation can be inspired and propagation under alternating stress caused by vibration. If amount of dislocation aggregation in machining layer, materials will be strengthen and the state will change from body material, which will lead to elastic deformation to reach the balance of stresses. In the other aspect, nonuniform distribution of organization always exists in materials. Stress concentration may also exist in some part of the material or micro areas. Under the effect of alternating stress, the structure will deform due to micro yield.

3. Experiment

3.1. Experimental materials

The material is Al alloy thick plate (7075-T651). The dimension is 500 mm×230 mm×60 mm. The thickness of machining wall is 2 mm. VSR is applied to the structures in different aging time. The micro structures of deformed parts are tested, observed and compared by electron microscope. Two types of structures are obtained by milling, as shown in figure 2(a) and figure 2(b). In order to reduce the addition deformation caused by the fixture, the part is fixed on the bottom by vacuum adsorption.
A test sample is cut from the bottom of the specimen. The cross section of the specimen is tested by using TEM scanning electron microscope to observe the generation of dislocation and grain deformation.

3.2. Vibration equipment and specimen.
The specimen is fixed on the vibration table. Rubber blankets are used as the elastic support of the vibration table. The rubber blankets are placed on the nodal points of vibration of the table, as shown in figure 3. The first order natural frequency acceleration of the vibration system is 67.0 m/s². Therefore, the exciting force is 2.7 KN (54.0 m/s²), which makes the vibration system work in sub-frequency resonance area. Three aging times (30 min, 60 min, 90 min) are applied to compare the results.

4. Experiment analysis

4.1. Distribution of the deformation
The deformation of the specimen before and after VSR is measured to compare the influences along the length direction. Figure 4(a) shows the deformation of X direction of three square structures with different aging time: 30 min, 60 min, 90 min. It can be seen that after 30 min VSR aging, the deformation increased 40 μm averagely, which indicates that the deformation is intensified in this period. After 60 min VSR aging, the deformation decreased 20 μm, which indicates that continuous aging decreased the deformation. The deformation curve becomes flat, this indicates that the bending and twisting of the structure are released. When the aging time extended to 90 min, the deformation of the structure increased obviously and became a bend curve. It can be concluded preliminarily that for this three square structure, 30 min is the best aging time to increase the dimensional stability.
Figure 4. Relative deformation along with X direction. (a) three square and (b) multi-square structure.

The comparison of the same experiment of multi-square structure is shown in figure 4(b). After 30 min and 60 min aging, the deformation increased significantly, which indicates the internal stress redistributed in this period. When the aging time extended to 90 min, spring back deformation can be observed, which indicates that the deformation became stable with the redistribution of internal stress. Therefore, 90min is the best aging time for multi-square structure to improve the stability. From the results, it can be seen that the deformation of the structure varies with different VSR aging time. Theoretically, the total intensity of initial stress and vibration stress cannot reach to plastic yield, so the deformation should be caused by the changes in micro areas.

4.2. metallographic analysis

Figure 5(a)-(d) shows the dislocation distribution of machining area by TEM.

Figure 5. Dislocation along with X direction profile (a) initial state, (b) 30min aging, (c) 60min aging and (d) 90min aging.
Figure 4 shows that dislocation density around grain boundary increases with the aging time. The vibration energy excited and increased the micro dislocation. The dislocation can be easily observed in the second phase. Microscopic hardening caused by the dislocation pinning in this precipitation strengthening phase increase the difficulty of plastic deformation. At the same time, this material hardening also leads to deterioration in machining layer and material behaviour change in some local place. This behaviour change is the main reason of elastic deformation of the structure.

Firstly, the vibration energy excited the internal dislocation which exists in most of manufacture process of plates with micro defect and inhomogeneity of structure. The observed dislocation pinning around machining layer corresponds to this process. Secondly, the nonuniform distribution of dislocation density leads to the nonuniform of material behaviour and the nonuniform of the micro intensity distribution in cross section. Thirdly, the dimensional stability is different for different shapes of structures in the same aging time by VSR. The aging time and process of VSR should be adjusted for different shapes to obtain the optimal dimensional stability.

5. Summary
The experiment results demonstrated the effectiveness of VSR to improve the dimensional stability of aluminum thin wall structures. The optimal aging time for different structures depends on both the structure shape and initial internal stress state.

6. Reference
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