Research Article

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Effects of TVSR process on the dimensional stability and residual stress of 7075 aluminum alloy parts

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Abstract: Residual stress generated during the blank forming and machining process significantly influences the dimensional stability of the mechanical parts. The equivalent bending stiffness and thermal vibration stress relief (TVSR) are two factors that affect the deformation of thin-walled workpiece. To increase the machining accuracy, on the one hand, increase the equivalent bending stiffness in manufacturing, and on the other hand, usually conduct the stress relief process to reduce the residual stress in manufacturing. In the present study, morphology optimization and TVSR process are conducted on a thin-walled part Specimen B of 7075 aluminum alloy to control the residual stress and machining deformation before finish machining. As a contrast, Specimen A is machined in one step. The deformations vary with time of Specimen A and B are measured. The corresponding finite element model is built to further study the stress and distortion during the machining process. Results showed that (1) deformation decreased with the increase of equivalent bending stiffness, compared with Specimen A, the maximum deformation of Specimen B decreased by 58.28%. (2) The final maximum deformation of Specimen B can be reduced by 38.33% by topology reinforcement to improve the equivalent stiffness and TVSR to reduce the residual stress.

Keywords: residual stress, TVSR, dimensional stability, machining deformation, FEM

1 Introduction

Residual stress is the internal stress for the self-equilibrium, which remains in the body after eliminating the external force or uneven temperature field [1]. The residual stress will inevitably be induced into the workpiece in the rolling, extrusion, casting, forging, welding, or machining process [2]. The stress state in the material significantly determines the mechanical behavior and fatigue life [3]. It is the reflection of strain energy that introduced the external energy field [4], and it reaches a steady state before the shape is changed again [5]. In the machining process, the stress is released and redistributed due to the removal of the material, which causes the dimension change of the workpiece [6].

The aforementioned dimension change is also known as machining deformation [7], which evidently decreases the manufacturing accuracy. To reduce the machining deformation, adding stiffeners to increase bending stiffness is the simple way to first think [8]. Li et al. investigated the influence of the equivalent bending stiffness on the machining deformation [9] and proposed a deformation control method based on enhancing the equivalent bending stiffness [10] of the thin-walled parts. It is revealed that the machining deformation decreases as the equivalent bending stiffness increase in the length direction. When the stiffening ribs are placed closer to the maximum deformation point, the deformation can be further reduced. In comparison to the traditional machining method, the final maximum deformation of the samples from Group 1 and Group 2 produced by the three-step method is reduced by 29.68 and 48.09%, respectively. Li et al. [11] found that bending stiffness affects the contribution of machining-induced residual stress (MIRS) and initial residual stress (IRS) to machining deformation of the thin-walled part.

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The relatively smaller equivalent stiffness leads to the more machining deformation contribution to the thin-walled part. Gao *et al.* [12] developed the influence of the work-piece position in the blank to the machining deformation. The results revealed that the symmetrical machining method is the most effective way to reduce the machining deformation.

Undoubtedly, residual stress is the primary cause of machining distortion [13], and the residual stress can be divided into two manufacture-induced and blank IRS [14]. In recent years, researchers are trying every trick in the book to eliminate the residual stress [15], and some of them have achieved good results [16]. Annealing treatment is a traditional but effective stress relief method [17,18], but it usually takes a lot of time energy to finish one process. Kim *et al.* [19] studied the effects of the annealing temperature and time on the residual stress relief, and the quantitative correlations between the annealing variables and the residual stress mitigation were obtained. Feng *et al.* [20] investigated the relationship between microstructure and residual stress of γ -TiAl alloy by molecular dynamics simulations, and they found that the fewer the point defects in the grain as long as the higher the annealing temperature. Dubois *et al.* [21] explored the residual stress relaxation and thermal stability of nanocomposite metals via time-resolved in situ annealing under synchrotron high-energy X-rays.

Song *et al.* [22] found that the grain refinement has occurred due to the residual stress as the driving force although a residual amount of the columnar microstructural architecture of α -Fe could be observed after the vacuum annealing treatment. Tong *et al.* [23] demonstrated that grain boundaries in the deformed NC a-iron evolve to a more equilibrium state during annealing, eliminating, or minimizing the residual stress. Fernández *et al.* [24] believed that below a certain treatment temperature (250°C), it is possible to identify an appropriate thermal treatment capable of relaxing residual stress in this composite while even increasing its yield strength. Sun *et al.* [25] demonstrated that residual stress magnitudes are significantly decreased and eliminated by novel multistage interrupted artificial aging treatment, while the traditional artificial aging only contributes to a reduction of 10–35%.

Vibration stress relief (VSR) is also an efficient method to control the residual stress. Compared with TSR, VSR is more high efficiency, environmentally safe, and energy saving. Gong *et al.* [26] presented that VSR significantly improved the shape and dimension stability of the thin-walled parts by relieving induced residual stresses. Li *et al.* [27] presented that the maximum residual stress of welded

DH36 steel tube is decreased by 47–49% after treated by VSR. Shalvandi *et al.* [28] demonstrated that after treated by ultrasonic stress relief (USR) with 24,500 Hz vibration frequency and 23–46 μm amplitude, the grain size does not change and the dislocation movement increases. Cai *et al.* [29] combined the traditional VSR with torsional vibration, and they found that the torsional vibration can induce coupled lateral torsional resonance and decrease the residual stress. Gao *et al.* [30] conducted residual stress measurement and fatigue tests to investigate the effects of VSR on the fatigue life and residual stress of 7075-T651 aluminum alloy, and the S–N curves and fatigue limit were obtained.

Wang *et al.* [31] concluded that the residual stress is released after treated by VSR. At the same time, the disintegration of “orientation of banding” and the decrease of dislocation density, the strain energy, and the fraction of low-angle boundaries within each type of grain orientation are observed. Wang *et al.* [32] also found that VSR vibration more than 10 min can weaken the basal textures of AZ31 Mg alloy. Vardanjani *et al.* [33] presented an analytical model on the basis of the plasticity theory with linear kinematic hardening to clarify the mechanism of release of residual stress under cyclic loading.

Moreover, Gu *et al.* [34] proposed a multidimensional ultrasonic stress relief (MDUASR) method and proved that the MDUASR has the evident effect on residual stress elimination and the MDUASR can increase the energy conservation compared with the MDUSR. Gong *et al.* [35] used a roll-bending process to eliminate the quenching residual stress in a large-size 2219 Al alloy ring, and the residual stress reduction rates of circumferential and axial are 61.72 and 86.24%, respectively. Colegrove *et al.* [36] reduced the residual stress of wire and arc additive manufacturing parts using high-pressure rolling with a “profiled” roller.

Thermal vibration stress relief (TVSR) is a novel stress relief method that has the advantages of both TSR and VSR and has a better stress relief effect than single TSR and VSR. Lv and Zhang [37] first validated the effectiveness of TVSR on the aluminum alloy. Gao *et al.* [38] further validated the stress-reduction effect of TVSR and investigated the stress relief mechanism of TVSR on 7075 aluminum alloy. They found that TVSR has a good stress reduction effect for peak stress, the reduction rates of TVSR are 38.56 and 20.43% higher than VSR and TSR, and it evidently increased the dislocation density. Chen *et al.* [39] concluded that for 2219 Aluminum Alloy Weldments, the temperature of 185°C at resonant frequency is more helpful to reduce transversal and longitudinal residual stresses by TVSR.

Figure 1: Size and shape of thin-walled specimen.

In recent years, TVSR has been widely concerned by scholars due to its high-efficiency, energy-saving, and environmental protection characteristics, and its stress relief effect has been verified on a variety of materials. However, most of the current researches are focused on the stress relief effect, and the research on the dimensional stability of structural parts after TVSR is rarely reported, and its effect on the dimensional stability also needs to be further verified. In the present study, the TVSR process is conducted on a thin-walled part of 7075 aluminum alloy to control the residual stress and machining deformation before finish machining. As a contrast, the other part is machined without a stress relief process. The blank IRS and the deformations after machining are measured. The corresponding finite element (FE) model is built to further study the stress and distortion during the machining process.

2 Experiments and simulations

In this study, three 7075-T6 aluminum (Al) alloy thick plates are used to prepare experimental specimens. One plate, whose size is 200 mm × 150 mm × 30 mm, is applied for residual stress measurement, and two plates, whose

size is 200 mm × 150 mm × 30 mm, are applied for machining and stress relief experiments.

2.1 Design of specimen

Machining deformation problem is more serious for thin-walled parts. Therefore, one type of thin-walled part is designed for the validation of residual stress and deformation control. The size and shape are shown in Figure 1. It is made of 7075-T6 Al alloy thick plates, and the material composition and mechanical properties are presented in Tables 1 and 2.

The residual stress that affects the manufacturing accuracy can be divided into IRS and MIRS. MIRS has a smaller depth but higher peak stress, and as a result, it significantly influences the final accuracy. The main MIRS is induced in the finish machining process, and the stress-reduction process is usually applied before the finish machining.

The traditional allowance design method only considers the increase of wall thickness; however, the overall stiffness is also critical to the deformation. Thus, in this study, the allowance is designed not only to reserve the material but also to increase the overall stiffness. Based

Table 1: Material composition of 7075-T6 Al alloy

Si (%)	Fe (%)	Cu (%)	Mn (%)	Mg (%)	Cr (%)	Zn (%)	Ti (%)	Al (%)
0.40	0.50	1.1–2.0	0.30	2.1–2.9	0.18–0.28	5.1–6.1	0.20	The rest

Table 2: Properties of 7075-T6 Al alloy

Density (kg·m ⁻³)	Elastic modulus (GPa)	Yield strength (MPa)	Poisson's ratio
2,810	71.7	518	0.33

on the original size and shape of the specimen, some extra materials are reserved as the machining allowance to improve the stiffness. In this situation, the finite element analysis (FEA) and topological optimization are combined to obtain the ideal allowance.

Optimization design is based on the mathematical programming theory, the optimization mathematical theory, computer and application software as tools, and fully considering a variety of design constraints to seek the best design to meet the predetermined objectives. For the structural optimization design, the topology optimization based on FEA is an effective method. The topology optimization takes the material distribution as the optimization object. Through the topology optimization, the best distribution scheme can be found in the design space of uniformly distributed materials. In the structure analysis, the topological optimization needs to be calculated by the FE method. An exponential approximation topology optimization problem can be defined as the following forms:

$$\left. \begin{aligned} \min_X: c(X) &= U^T K U = \sum_{e=1}^N (x_e)^p u_e^T k_0 u_e \\ \text{subject to: } \frac{V(X)}{V_0} &= f \\ K U &= F \\ 0 < X_{\min} \leq x &\leq 1 \end{aligned} \right\}. \quad (1)$$

U and F represent the global displacement vector and force vector, respectively, and K is the global stiffness

matrix of the structure. X is the design variable and represents the density of the material at each location. The objective function is to minimize the deformation energy of the structure under external load. The constraint conditions are the optimized volume fraction f in the design domain, and the optimized density is between $X_{\min}$ and 1.

According to the relative basic theory, the deformation caused by residual stress can be equivalent to the bending distortion caused by the uniform bending moment on the two opposite edges. Hence, FEAs under two load conditions (bending loads in length and width direction) are established using Hyperworks software as the basic model. The deformation is set as the optimization constraints, and the minimized element density is set as the optimization objective. The morphology of the material can be obtained by iterative calculations using Optistruct modular of Hyperworks, as shown in Figure 2. According to the optimization results, the optimized specimen can be obtained, and the specimens before (Specimen A) and after (Specimen B) optimization are presented in Figure 3.

2.2 Experiments

Specimen blanks are purchased from Tianjin Dongfang Hanyu Technology Development Co., Ltd. The blanks come from the same batch of 7075-T6 Al alloy forging

Figure 2: Iterative process of topology optimization. (a) Iteration 15, (b) iteration 30, (c) iteration 45, and (d) iteration 63.

Figure 3: Iterative process of topology optimization.

plate. The blanks size is 300 mm × 150 mm × 30 mm rectangle plates. Prism residual stress measurement device (Stress tech Group) and layer removal method are used to measure the blank IRS. The X direction is the rolling direction. The residual stress in each layer of the plate is shown in Figure 4. From Figure 4, we can see the IRS in X and Y directions is different. The main reason for such phenomenon is as follows. During the forming process of the blank, the cooling of each part of the blank is uneven, resulting in temperature difference and thereby residual stress. For the specimen in the study, the blank is the rolling plate and the X direction is the rolling direction. For the Y direction, the edge is cooled first, and the middle part is still at high temperature, so the temperature gradient in the Y direction is larger, and the residual stress caused by the temperature gradient is larger, while the temperature in the X direction is more uniform than that in Y direction, and the temperature gradient is smaller than that in the Y direction, so the residual stress is smaller.

Figure 4: Residual stress in each layer of the plate.

The specimens are machined using Fage 650 machining center (Jinan Fage CNC Machinery Co., Ltd) and four-edge carbide end cutting cutters. No. 5 white oil is used as a coolant. The feed rate, spindle speed, cutting depth, and cutting width are 3,500 rpm, 9,000 mm·min⁻¹, 0.3 mm, and 3 mm, respectively.

To reduce the effect of the clamping force on the plate deformation, AB glue (acrylic-modified epoxy resin mixed with modified amine hardener) is used to fix the workpiece on a steel rectangular base plate, and the four corners of the rectangular base plate are fixed on the machine tool workbench with pressing plates.

Specimen A is directly cut from blank to type A as shown in Figure 3 without any other process. Compared with Specimen A, for Specimen B, the first step is blank cutting to Type B, and then 96 h later, TVSR is carried out. The aging temperature is 175°C. First, the specimen is heated to 175°C in 0.5 h and preserved for 0.5 h. Then, a 5 min VSR process with the frequency of 60.1 Hz and eccentric motor speed of 3,606 rpm is conducted. After the vibration process, it is preserved for 0.5 h at 175°C and then another 5 min vibration process is carried out. Finally, after cooling in the furnace for 4 h, the fixture is removed and Specimen B (Type A) is air cooled to room temperature. The machining process is shown in Figure 5a, the TVSR platform is shown in Figure 5b, and the TVSR process flow chart of Specimen B is shown in Figure 6.

The distortion measurement of the bottom surface of Specimen A is carried out after the end of the cutting 24, 72, 96, 144, 168, 288, and 312 h, respectively (Figure 7a). The deformation measurement of the bottom surface of Specimen B is carried out after the end of the first cutting 24, 72, and 96 h and after the end of the second cutting 24, 48, and 72 h, respectively (Figure 7b). The distribution of measuring points is shown in Figure A1 in the Appendix.

Figure 5: (a) Machining experiments and (b) TVSR platform.

The deformation measurement equipment is Croma 10158 CMM (Shenzhen Surrey Measurement Technology Co., Ltd.) (Figure 7c), and the measurement software is PC DMIS. The measurement accuracy of CMM is characterized by the maximum allowable error of length measurement (MPEE), that is, linear error or length error. The MPEE of Croma 10158 CMM is $3.0 + 1 L/300 \mu\text{m}$.

The experiments (including cutting and TVSR) and deformation measurement of specimens are performed in Anhui Chungu 3D printing Intelligent Equipment Industry Technology Research Institute (Wuhu City, Anhui Province, 118.20°E, 31.08°N). The time period of experiments and deformation measurement is from May 2019 to June 2019.

Figure 6: TVSR process flowchart of Specimen B.

Figure 7: Deformation measurement of Specimen (a) A and (b) B, and (c) Coordinate measuring machine.

The indoor temperature is 18–25°C, and the relative humidity is 40–60%.

2.3 Simulations

The equivalent bending stiffness is obtained by FE simulation. In the Design Moduler of Workbench 19.0, 3D parameterized model of specimen is established. Material properties of the FE model are presented in Table 2. Zero is applied to the displacement in three directions to the face parallel to the YZ plane and then applied to evenly distributed load q_x in the Z direction to the other face (Figure 8). So, from the solution of deformation in the static analysis, maximum deformation dis_x is calculated along the X direction. Similarly, maximum deformation dis_y along the Y direction is calculated (Figure 8).

Therefore, the equivalent bending stiffness of thin-walled parts in the X and Y directions can be calculated on the basis of the results of the FE simulation and equations (2)–(5) [11].

Figure 8: FEM boundary conditions for equivalent stiffness calculation.

Figure 9: FEM boundary conditions for machining deformation calculation.

$$h_{eqvx} = \left(\frac{4F_x L^3}{dis_x \cdot E \cdot W} \right)^{\frac{1}{3}}, \quad (2)$$

$$h_{eqvy} = \left(\frac{4F_y W^3}{dis_y \cdot E \cdot L} \right)^{\frac{1}{3}}, \quad (3)$$

$$D_{eqvx} = \frac{E \cdot h_{eqvx}^3}{12(1 - \mu^2)}, \quad (4)$$

$$D_{eqvy} = \frac{E \cdot h_{eqvy}^3}{12(1 - \mu^2)}, \quad (5)$$

where h_{eqvx} (h_{eqvy}) and D_{eqvx} (D_{eqvy}) are the equivalent thickness and equivalent bending stiffness in the X and Y directions, respectively; L and W are the length and width of the rectangular part, respectively; $F_x = q_x \cdot W$; and $F_y = q_y \cdot L$.

Deformation simulation FE models of specimens are built by workbench 19.0 (Figure 9). The geometry model consists of two parts: the final specimen and the material to be removed. The geometry model is imported into Workbench 19.0. Then, the geometry model is evenly divided into 30 layers. Solid 186 element is selected as

the FE type. The elastic constraint to the face is applied parallel to the YZ plane. The material properties of the FE model are presented in Table 2. The IRS is assigned to each layer by utilizing “Inistate” function. Then, “kill” element has to be removed with element birth and death technology layer by layer (“kill” element means assignment 0 to element stiffness, unit load, mass, and so on. The killed element mass and energy will not be included in the results of model). As a consequence, deformations and stress are obtained.

3 Results and discussions

The simulation results of equivalent stiffness before and after topology optimization are presented in Figure 10 and Table 3. It can be seen from Figure 10 and Table 3, compared with Specimen A (before optimization), the equivalent bending stiffness D_{eqvx} in the X direction and D_{eqvy} in the Y direction of Specimen B (after topology optimization) is increased by 123.66 and 108.93%,

Figure 10: Simulation results of equivalent bending stiffness for Specimen A in the X direction (a) and the Y direction (b) and for Specimen B in the X direction (c) and the Y direction (d).

Table 3: Comparison of equivalent bending stiffness and material removal ratio

Comparison	Specimen A	Specimen B	Increase percentage
D_{eqvx} (N-mm)	3.72×10^6	8.32×10^6	+123.66
D_{eqvy} (N-mm)	4.37×10^6	9.14×10^6	+108.93
Material removal ratio	82.94%	76.11%	-6.82

respectively; compared with Specimen A, the material removal ratio of Specimen B is reduced by 6.82%.

The simulation results of deformation and stress of Specimen B after the first cutting are shown in Figure 11. It can be seen from Figure 11 that the maximum deformation is 0.16 mm, the maximum stress in the X direction is 81.84 MPa, and the maximum stress in the Y direction is 49.38 MPa. It can be seen that there is still a large residual stress in the specimen after the first cutting.

Vertexes and maximum point as a typical point are taken to analyze the whole deformation. Thus, the average value of four corner point on the bottom surface (namely four vertexes), maximum point, the average value of P1 and P7 (P1–P7), and average value of P30 and P33 (P30–P33) as the typical point for Specimens A and B. The deformation comparison of Specimen A of 24, 72, 96, 144, 168, 288, and 312 h after the end of the cutting

is shown in Figure 12(a). The deformation comparison of simulation and experiment of Specimen B of 24, 72, and 96 h after first cutting, and 24 h (124 h), 48 h (148 h), and 72 h (172 h) after second cutting are shown in Figure 12(b).

Figure 12(a) shows that, 24, 72, 96, 144, 168, 288, and 312 h after the end of the cutting, the maximum deformations of Specimen A are 0.317, 0.399, 0.385, 0.376, 0.371, 0.362, and 0.356 mm, respectively; the average values of vertexes are 0.128, 0.163, 0.167, 0.188, 0.188, 0.190, and 0.186 mm, respectively. Within 72 h after machining, the deformation changes obviously. After 72 h of machining, the dimension of Specimen A tend to be stable, and the deformation variation in unit hour is less.

Figure 12(b) shows that the simulation results are in accordance with the experimental results. 24, 48, and 96 h after first cutting, the maximum deformations of Specimen B are 0.132, 0.144, and 0.149 mm, respectively; the average value of vertexes are 0.064, 0.059, and 0.062 mm, respectively. 24 h (124 h), 48 h (148 h), and 72 h (172 h) after second cutting, the maximum deformations of Specimen B are 0.216, 0.207, and 0.220 mm, respectively; the average values of vertexes are 0.153, 0.148, and 0.155 mm, respectively. After removing the topological optimization allowance in the second cutting, the maximum deformations of Specimen B increased by 0.084 mm (24 h), 0.063 mm (48 h), and 0.071 mm (72 h), and the average deformations of the vertexes increased

Figure 11: Simulation results of deformation and stress of Specimen B after first cutting.

Figure 12: Comparison of deformation vary with time: (a) Specimen A and (b) Specimen B.

by 0.089 mm (24 h), 0.089 mm (48 h), and 0.094 mm (72 h), respectively.

Compared with Specimen A, it can be seen that the equivalent bending stiffness of Specimen B is improved due to the topological optimization. Twenty-four hours after the first cutting, the maximum deformation of Specimen B decreased by 58.28% than that of Specimen A, the average value of vertexes deformation of Specimen B decreased by 49.96% than Specimen A. After second cutting, the deformations of Specimen B are increased. This presents that 72 h after first cutting, although the stress has reached a relatively stable state, there is still a certain stress concentration inside the specimen especially in the area to be removed.

Take the deformation of 312 h after the end of cutting of Specimen A, and 72 h after second cutting of Specimen B as the final deformation, the final maximum deformation of Specimen B is 38.33% less than that of Specimen A, and the final average deformation of the vertexes is less than 16.34%.

4 Conclusion

In the present study, the deformation and dimension stability of two thin-wall parts of 7075 Al alloy with different equivalent bending stiffness are studied. Topological optimization is carried out on the basis of Specimen A to improve the equivalent stiffness, the specimen after optimization as Specimen B. Specimen A is one time cutting to the final shape, and after Specimen B first cutting 96 h, the TVSR is conducted to control the residual stress and machining deformation. Then, the second cutting is implemented. The deformation vary with time are measured within 312 h after the end of cutting of Specimen A, the deformations that

vary with time are measured within 96 h after first cutting and 72 h after second cutting of Specimen B. By comparing the deformation and dimension stability of Specimens A and B, the following conclusions are obtained.

- (1) After topological optimization, the equivalent bending stiffness D_{eqvx} in the X direction and D_{eqvy} in the Y direction of Specimen B (after topology optimization) is increased by 123.66 and 108.93%, respectively; compared with Specimen A (before optimization), the material removal ratio of Specimen B (after topology optimization) is reduced by 6.82%.
- (2) Deformation decreased with the increase of equivalent bending stiffness. After first cutting, compared with Specimen A, the maximum deformation of Specimen B decreased by 58.28%, the average value of P30 and P33 decreased by 94.11%, and the average value of vertexes decreased by 49.96%.
- (3) From the simulation results, it can be seen there is still a large residual stress in the specimen after the first cutting. The maximum stress in the X direction is 81.84 MPa, and the maximum stress in the Y direction is 49.38 MPa.
- (4) From the comparison of Specimens A and B, the maximum deformation of the part can be reduced by 38.33% by topology reinforcement to improve the equivalent stiffness and TVSR to reduce the residual stress.

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Appendix

Figure A1: Deformation measurement point.