Effect of vibrations on the residual stress field formation during milling of high-strength aluminum alloys

A Yu Nikolaev
Irkutsk National Research Technical University, Lermontov Str., 83, Irkutsk, 664074, Russia
E-mail: andrnikolajev@gmail.com

Abstract. The authors examine the influence of high-speed milling on the distribution of residual stresses in parts made of structural high-strength aluminum alloys Al-Cu-Mg, which are the main structural materials in the aerospace industry. Milling was carried out at high cutting speeds. Different tool settings were used to balance the instrument. Plastic deformation occurred in the part’s surface layers. Residual stresses were measured by the X-ray method. It was found that high-speed milling creates residual compressive stresses that are favorable for the operation of the part. The depth of the residual stresses depends on the cutting mode. The article shows the relationship between residual stresses and the type of metalworking tool, processing conditions in structural parts made of high-strength aluminum alloys.

1. Introduction
The competitiveness of aviation technology depends on the quality of materials used in its designs. Aluminum alloys are still the main material for airplane gliders since they have low density, high specific strength, good corrosion resistance, and are easily deformed. Milling is the primary manufacturing method for modern aircraft parts. When milling high-strength aluminum alloys, machining is carried out at high speeds, and, consequently, at high rotation frequency speeds [1, 2].

The metalworking tool, depending on the milling parameters, causes plastic deformation of the surface layers of the material to be processed and its hardening – peening. The hardening of the part’s surface layer determines its operational characteristics: work hardening increases wear resistance and fatigue strength. An increase in the thickness of the work-hardened layer leads to an increase in reliability and durability.

Insufficient cooling and heat removal from the cutting zone with chips released during milling leads to softening under the influence of high temperatures in the subsurface layers of the part material. Mechanical loads lead mainly to compressive stresses, while heating leads to tensile stresses. The combination of mechanical and thermal loads determines the final stress-strain state of the part.

Residual plastic deformations arising during machining cause a change in the linear dimensions of the milled surface layer of the part. However, the underlying elastically stressed layers of the part’s material, with which the upper hardened layer is inseparably connected, counteract the noted changes. For this reason, residual stresses of opposite sign (σ₂) arise, the value of which can reach the ultimate strength (σₐₚ) of the processed material.

Tool vibrations during milling also affect formation of inhomogeneous residual stress field. The influence of residual stresses in thin-walled long structures is especially important, because the changes
that residual stresses introduce into the metal are the cause of many rejects. The research was carried out to determine the influence of cutting conditions, vibrations on residual stresses in the surface layer of the part.

2. Experimental technique
The machining was carried out on HSC 75V linear milling center. Plates of aluminum alloys were milled in different modes. Residual stresses in the milled plates were determined by the X-ray method.

2.1. Milling
The material of the investigated parts is V95pch, 1163 and 1933 alloys after heat treatment according to the T2 mode. For mechanical properties of high-strength aluminum alloys, see table 1 [3-5].

| Table 1. Mechanical properties of high-strength aluminum alloys. |
|---------------------------------------------------------------|
| Alloy       | σ_b (MPa) | σ_0.2 (MPa) | δ (%) | K_{IC} (MPa · m^{1/2}) |
| 1933        | >520-540 | >420-460 | ≥7   | ≥37                      |
| V95pch      | ≥500-540 | ≥420-460 | ≥7   | ≥34                      |
| 1163        | >430     | 340-380  | ≥15  | 145                      |

Cutting parameters of V95pch and 1163 alloys are shown in table 2.

| Table 2. Cutting data.       |
|-----------------------------|
| Parameter       | Range                  |
| Cutting speed, v_c       | 1500 m/min             |
| Feed per tooth, f_z      | 0.25 mm                |
| ADOC, a_p              | 0.5 mm                 |
| RDOC, a_e              | 30 mm                  |
| Coolant            | Emulsion               |

When milling parts from alloy 1933, the feed was increased. The cutting tools were attached to the HSK63 tool holder. When milling parts from alloys 1163 and V95pch, a body milling cutter with replaceable carbide inserts was used. Tool setting includes elements of the Capto C5 system: basic holder C5 for HSK-63A tool cone with a sleeve for internal coolant supply and R790-032C5S2-16M cutter with replaceable carbide inserts R790-160408PH-NM H13A [1,2,6].

For high-speed milling of 1933 alloy parts, an AZ-3D16R6L65 solid carbide cutter was used. The balancing of the tool setting was carried out. The vibration was monitored, the roughness of the treated surfaces was measured according to known methods [1, 2, 6-10]. To measure the cutting forces, a Kistler 9253B23 dynamometric complex was used. The plate thickness after high-speed milling was 5 mm.

The measurement of the surface roughness after processing was carried out with a Taylor & Hobson Form Talysurf i 200 profilometer. Surface roughness affects the accuracy of determining residual stresses, because is the cause of change in the angle of X-rays incidence. The roughness value of the analyzed surface should not exceed the minimum value of the effective penetration depth of X-rays. The roughness of the workpieces surface is presented in table 3.

| Table 3. Roughness of machined surfaces of aluminum alloys. |
|-----------------|
| Roughness        | Alloy  |
|-----------------|--------|
| 1933            | V95pch | 1163   |
| Ra (micron)      | 0.0900…0.6300 | 0.2348…0.2708 | 0.4948…0.4975 |
2.2. Method for determining residual stresses

Residual stresses in the subsurface zone were measured on the milled surfaces. Residual stresses were measured with an XStress 3000 G3R / G3R X-ray diffractometer (figure 1). The residual voltage measurement circuit is shown in figure 2.

![Figure 1. Diffractometer XStress 3000 G3R/G3R (φ=+45°): 1 – X-ray tube; 2, 3 – position-sensitive detectors A and B; 4 – collimator; 5 – investigated surface.]

![Figure 2. Residual voltage measurement.]

When shooting with this diffractometer, the goniometer tilt angles χ are used instead of ψ (the angle between the normal to the sample surface and to the reflecting plane (hkl)). The analysis of residual stresses was carried out using the sin² ψ method using the reflection plane (311). The studies of triaxial stresses were carried out in accordance with the requirements of EN 15305:2008 [11-18]. X-ray parameters: Cr-Kα-radiation, wavelength (λ) – 0.22909 nm; vanadium filter; collimator – 3 mm; two position-sensitive detectors A and B, located symmetrically. The method for determining the position of the diffraction peak is Cross correlation. For the automated calculation of stresses, the values of Young’s modulus (72 GPa for V95pch and 1933; 69 GPa for 1163) and Poisson’s ratio (0.345 for V95pch and 1933; 0.31 – for 1163) were set in the diffractometer program.

The penetration depth of X-ray radiation (Z) for the χ-modified goniometer was calculated using the formula (1):

$$ Z = \frac{\cos 2\theta \cos \chi}{\mu \sin \theta (\cos 2\theta - 1)} $$

where θ is the diffraction angle; μ is X-ray attenuation coefficient; (hkl) is reflective plane; χ is the angle of rotation of the plane containing the incident and reflected X-rays.

X-ray attenuation coefficient (μ) was calculated using the formula (2):

$$ \frac{\mu}{\rho} = \sum_i a_i \frac{\mu_i}{\rho_i} $$

where i is the number of components; a_i is mass fraction of the component; \( \rho_i \) is density of each chemical element of the alloy; \( \rho \) is the density of the alloy; \( \mu_i \) is the X-ray attenuation coefficient of each component.

The chemical composition of the alloys was determined with a portable X-ray fluorescence analyzer (XRF spectrometer) S1 TITAN. For the chemical composition of aluminum alloys, see table 4. Table 5 shows the parameters of X-ray photography and the depth of penetration of X-rays.
Table 4. Chemical composition of high-strength aluminum alloys.

| Alloy | Mass fraction of elements (%) |
|-------|--------------------------------|
|       | Zn  | Cu  | Mg  | Mn  | Fe  | Si  | Zr  | Ti  | Al  |
| 1933  | 7.20| 1.20| 2.20| -   | ≤0.15| ≤0.10| ≤0.15| <0.06| 89.80 |
| V95pch| 6.76| 1.92| 1.47| 0.3 | 0.27| 0.09| -   | 0.04| 88.91 |
| 1163  | 0.07| 5.03| 1.37| 0.72| 0.14| 0.07| -   | 0.04| 99.52 |

Table 5. Parameters of X-ray imaging of milled aluminum alloy plates.

| Alloy   | Phase           | x-ray     | hkl | μ (1/mm) | Penetration depth X-ray radiation (μm) | ψ=0° | ψ=45° |
|---------|-----------------|-----------|-----|----------|---------------------------------------|------|-------|
| V95pch  | α-solid solution| Cr-Kα      | 311 | 44       | 10.5                                 | 7.4  |       |
| 1933    |                 |           |     | 43       | 10.7                                 | 7.6  |       |
| 1163    |                 |           |     | 42       | 10.2                                 | 7.2  |       |

The areas intended for measuring residual stresses were electrolytically etched and polished using a Lectropol-5 device. The thickness of the layer removed during electrolytic treatment was measured with a dial gauge. In the analysis of 1933 alloy plates, the residual stresses were measured without oscillation due to the excellent surface quality. In parts made of alloys V95pch and 1163, to increase the measurement accuracy, we used oscillation along the tilt angles of the goniometer χ=±5°.

3. Results and discussion
Residual stresses were measured in three different directions φ (figure 2). The azimuth angle φ = -40° (or “φ = -45°”) coincides with the direction of milling. Residual stress measurement results are shown in figures 3-5.

Figure 3. Residual stress diagram after milling of 1933 alloy parts. a – normal stresses; b – shear stresses; c – FWHM.
Residual stress measurements were stopped after reaching a depth at which stresses are zero or become tensile in one or more measured directions. Thus, after milling a part made of V95pch and 1163 alloys, the maximum depth of residual stresses was about 40 microns and made of 1933 – 120-140 microns. After milling into the part, the maximum compressive stresses lie below the surface. A low milling speed leads to the formation of compressive stresses at a depth: up to -114 MPa at a depth of up to 0.010 mm (V95pch alloy), up to -176 MPa at a depth of up to 0.022 mm (alloy 1163). Distribution of residual stresses is uneven.

High speed milling contributes to a more even distribution of residual stresses at greater depths. Obviously, increasing the cutting speed (vc) leads to higher compressive residual stresses. In alloy 1933, the value of compressive stresses is -150 MPa at a depth of up to 0.150 mm. In all cases, significant shear stresses of different signs are determined, which indicates significant plastic deformation of the material being processed.

As can be seen from table 3, the surface roughness (Ra) is less than the minimum X-ray penetration depth. For this reason, the roughness, in our case, does not have any effect on the measurement accuracy of residual stresses.

The FWHM parameter – the broadening of the diffraction peak at half its height – is an indirect characteristic of the hardening degree. The value of the FWHM parameter depends on the X-ray modes, properties, and structure of the material. An increase in the value of the FWHM parameter indicates work hardening.
4. Conclusion
The results presented in this article show the dependence of residual stresses on processing parameters. Obviously, the type of tool, its balancing and the chosen milling strategy have a greater influence on the level of residual stresses.
Favorable residual compressive stresses act in the surface layers of the aluminum alloy workpiece to be milled. Vibrations generated during milling affect the profile and depth of residual stresses in the subsurface zone of aluminum parts.

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