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# STRESS-STRAIN STATE OF FORMING TOOLS DURING COLD HEADING OF ALUMINUM ALLOY RIVETS

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## ABSTRACT

*This study investigates the stress–strain state of forming tools during the cold heading of rivets manufactured from A1050 commercial aluminum, A5056 aluminum alloy, and high-strength A2024 Al–Cu–Mg alloy. Particular attention is given to the influence of interference fit between the punch, die, and die sleeve on stress distribution within the tooling system. The cold heading process was analyzed using the finite element method (FEM), and the numerical predictions were validated through experimental measurements. Good agreement was obtained between the simulation and experimental results, confirming the reliability of the numerical model. The analysis showed that an interference fit in the range of 0.10–0.15 mm generated favorable compressive stress fields in the punch and die, thereby reducing tensile stress concentrations and enhancing tool strength and service life. The findings provide a practical basis for optimizing interference-fit design in cold heading tools used for aluminum alloy rivet manufacturing and contribute to improving tool durability and production efficiency in industrial forming processes.*

***Keywords:*** *aluminum alloys; cold heading; finite element method; interference fit; rivets; stress–strain state; tool life.*

## Introduction

Aluminum alloys are widely recognized as dominant structural materials in the aerospace industry due to their favorable combination of low density, good manufacturability, and excellent corrosion resistance. These materials are extensively used in the fabrication of aircraft load-bearing components, including fuselage skins, frames, main beams, ribs, as well as fuel and oil tanks. Their high electrical conductivity and relatively good machinability further enhance their applicability in aerospace engineering, which explains the continuous growth in their production and utilization (Storozhev & Popov, 1971).

One of the primary methods for joining aluminum aircraft structures is riveting (Belov & Ivanov, 2018). Rivet materials must satisfy several stringent requirements, including minimum weight, high shear and torsional strength, corrosion resistance, and suitability for mass production (Romanovskiy, 1979). Riveted joints exhibit high reliability under static, cyclic, and vibration loading conditions, while also minimizing deformation of structural components during assembly (TU 113-08-553-84, 1984). At the Aviastar-SP manufacturing plant, more than 350,000 MS20426 rivets made of A5056 aluminum alloy were used in the assembly of the MS-21 wing, accounting for approximately 23% of all fastening elements (Khas'yanova et al., 2021). In large-scale modern aircraft structures, the number of rivets is significantly higher; for example, approximately 1,800,000 rivets are used in the Il-62 aircraft and about 1,300,000 in the Il-18 aircraft (Khas'yanova et al., 2021).

Currently, cold forming remains one of the most widely used methods for rivet production due to the simplicity of the technological process and equipment, as well as its flexibility in manufacturing fasteners for fixed joints and its high technological efficiency. Although riveted joints are increasingly being replaced by advanced joining techniques such as welding, riveting remains indispensable in many engineering applications (Gurevich & Kolmakov, 2015).

However, cold forging tools are subjected to significant cyclic loading, which leads to fatigue failure, particularly in regions of stress concentration. Industrial statistics indicate that up to 30% of tool failures are caused by cracking in punches and dies, while approximately 25% are attributed to surface wear of the punch working surfaces. The primary mechanisms responsible for tool failure in cold forming processes are wear and fatigue-induced damage due to high cyclic stresses.

The durability of forming tools can be improved by optimizing their stress state. Tensile stresses are typically mitigated by Tensile stresses can be reduced by press-fitting the carbide punch and die inserts into steel sleeves with an appropriate interference (Gurevich & Kolmakov, 2015). Although this technology has been well developed in practice, the rational selection of interference values and their influence on the stress-strain state of tools during rivet forming from specific aluminum alloys remains insufficiently investigated and requires further study (Petrov et al., 2021; Vu Trong Bach et al., 2019; Vu Trong Bach et al., 2020).

## 1. Materials and Methods

The objective of this study was to analyze the stress-strain state of forming tools during the cold upsetting of rivets of aluminum alloys and to determine an appropriate interference fit between the punch-die assembly and the die sleeve in order to improve tool durability.

To achieve the research objectives, this study focuses on the following:

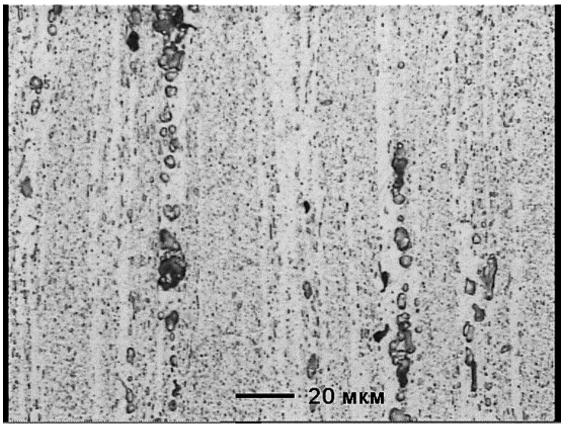
The study was conducted with the following main tasks:

- The stresses generated in the deformation zone of the workpiece and within the forming tools were determined using numerical simulation with QForm 11.2.400.3 software.
- The influence of forming speed on the workpiece temperature and strain rate was analyzed.
- The relationship between stresses in the die and the interference fit between the die and the die sleeve was established.
- The accuracy of the developed model was evaluated by comparing the energy and force parameters of the forming process obtained from simulations and experimental results.
- Technical recommendations were proposed to optimize the interference fit in order to enhance tool durability.

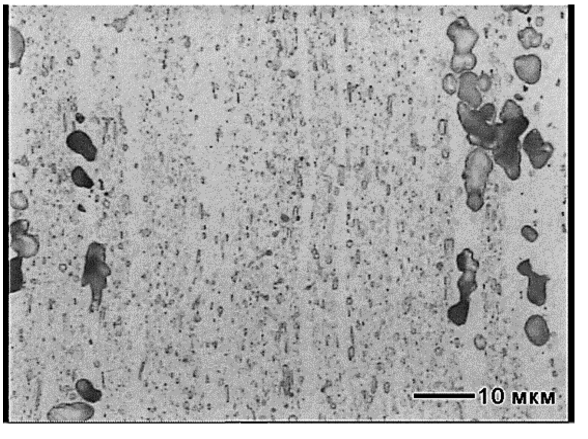
### Materials

Aluminum alloy A5056 is a non-heat-treatable work-hardening material consisting primarily of aluminum with 4.8-5.8% magnesium. It is characterized by low density, moderate tensile strength, high corrosion resistance, and good weldability. Owing to its combination of strength, ductility, and good formability, A5056 is widely used in the aerospace and rocket industries, particularly for the manufacture of structural shells, welded assemblies, and components subjected to medium loads in aggressive environments where lightweight and durable materials are required.

The material investigated in this study was A5056 aluminum alloy with the following chemical composition: Mg - 4.8-5.8%; Mn - 0.3-0.8%; Fe - 0.5%; Si - 0.5%; and Al - 92.4-93.7%. The initial grain size was 10-20 μm (Figure 1), and the mechanical and physical properties of the A5056 alloy are presented in Table 1.




a)




b)

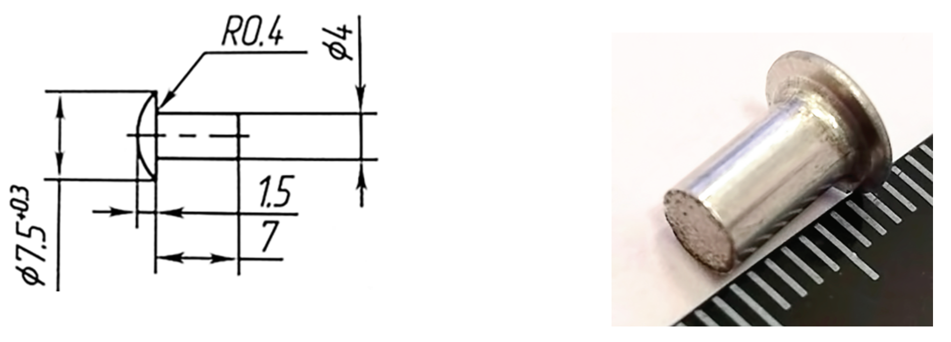
**Figure 1.** Microstructure of A5056 aluminum alloy (a - ×500, b - ×1000)

**Table 1.** Mechanical and physical properties of A5056 aluminum alloy

| No. | Property | Value |
|---|---|---|
| 1 | Density ρ, kg/m³ | 2560 |
| 2 | Melting temperature Tm, °C | 570-640 |
| 3 | Thermal conductivity λ, W/(m·K) | 112 |
| 4 | Ultimate tensile strength σb, MPa | 275 |
| 5 | Yield strength σ0.2, MPa | 130 |
| 6 | Elongation δ, % | 12-15 |
| 7 | Reduction of area ψ, % | 20-25 |
| 8 | Young's modulus E, MPa | 70 × 10³ |
| 9 | Hardness, HB | 65 |

**Research Methodology**

The object of investigation was the cold forging process of round-head rivets (Figure 2). The initial billet had a cylindrical shape with a diameter of 4 mm and a length of 10.85 mm. It was manufactured from A5056 aluminum alloy and processed according to the forging scheme illustrated in Figure 3.




a) b)

**Figure 2.** Rivet (a - technical drawing; b - finished product)

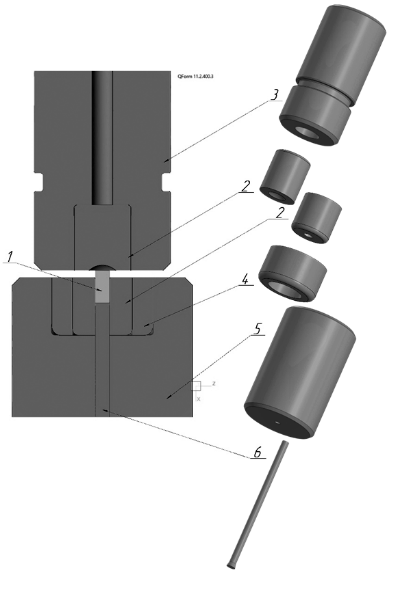



**Figure 3.** Rivet upsetting scheme

*(1 - Billet; 2 - Tool (punch-die set); 3 - Punch sleeve; 4 - Die sleeve; 5 - Die housing; 6 - Ejector)*

**2. Experimental Results**

In the experimental setup, components 3, 4, and 5 were manufactured from medium-alloy structural steel with high carbon content, while component 2 was made of hard alloy grade VK8-VK15. The hardness of the working surfaces reached up to HRA = 89.

To accurately simulate the material deformation process, an A5056 aluminum alloy material model was developed in MATLAB based on experimental data obtained from United Engine Corporation (Russian Federation). This model was constructed by combining experimental results with numerical simulation approaches. The methodology involved compressive testing of cylindrical specimens using a universal testing machine within a temperature range of 20-450 °C and strain rates of 0.001-0.4 $s^{-1}$.

Processing of experimental data using averaging techniques in QForm allowed the construction of isothermal flow stress curves, which were further corrected to account for frictional contact effects and thermal softening due to plastic deformation. The material behavior was approximated using the Hensel-Spittel constitutive model. The accuracy of the model was verified, with deviations from experimental data not exceeding ±2.5%:

$$\sigma_i = A.e^{m_1.T}.T^{m_9}.\varepsilon^{m_2}.e^{m_4/\varepsilon}.(1+\varepsilon)^{m_5.T}.e^{m_7.\varepsilon}.\dot{\varepsilon}^{m_3}.\dot{\varepsilon}^{m_8.T} \quad (1)$$

where A, m1, $m_2$, $m_3$, $m_4$, $m_5$, $m_7$, $m_8$, and $m_9$are coefficients determined by the least squares method using MATLAB. The resulting coefficients are presented in Table 2.

**Table 2.** Mathematical coefficients of the material model

| Temperature range (°C) | A | $m_1$ | $m_2$ | $m_3$ | $m_4$ | $m_5$ | $m_7$ | $m_8$ | $m_9$ |
|---|---|---|---|---|---|---|---|---|---|
| **20-450 °C** | 184.24 | −0.0026 | −0.1056 | −0.0242 | −0.0551 | −0.0034 | 0.4393 | 0.0003 | 0.1728 |

The numerical simulation of the cold upsetting of rivets was carried out using QForm 11.2.400.3, taking into account heat generation induced by plastic deformation. The simulation was performed as a three-dimensional finite element problem with an approximately 200,000-element mesh.

To describe the contact interaction between the billet and the tooling, the Leonov friction law was applied with a friction coefficient of 0.2. The main investigated parameters included the interference fit between the punch, die, and die sleeve, which was varied from 0 to 0.2 mm, as well as different materials (A1050, A5056, A2024) using the developed constitutive model.

Experimental rivet upsetting tests were conducted on a universal testing machine with a maximum load capacity of 250 kN at a displacement rate of 0.033 mm/s. The load-stroke curves were recorded, and a 3D-printed polylactic acid (PLA) centering fixture was used to ensure precise tool alignment during the experiments.

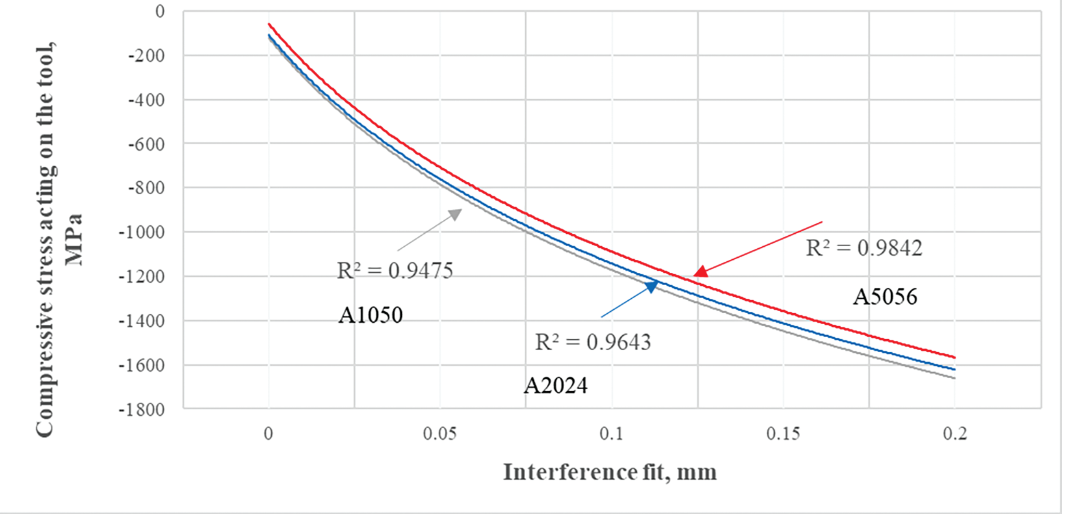
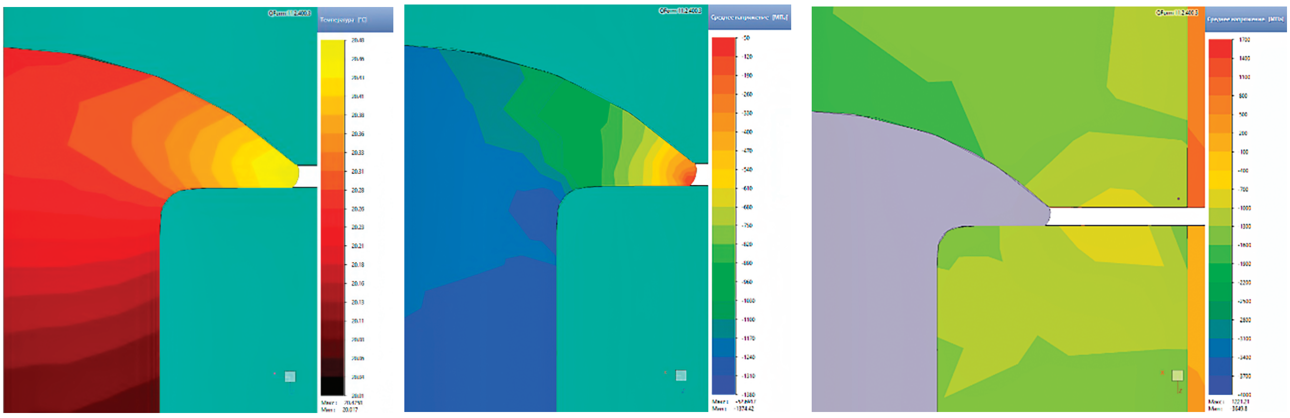



**Figure 4.** Relationship between compressive stress in the die sleeve and interference fit for different rivet materials

As shown in Figure 4, increasing the interference fit in the range of 0.05-0.15 mm leads to a significant increase in compressive stresses within the die assembly. Consequently, the overall tensile stress level is reduced, thereby decreasing the risk of fatigue failure of the tooling system.

A more detailed analysis of the stress-strain state of the forming tools was conducted using the riveting of A5056 aluminum alloy with an interference fit of 0.1 mm as a representative case. The simulation results indicated a maximum forming load of 48 kN. Under a low forming speed condition (2 mm/min), corresponding to the experimental testing machine regime, the workpiece temperature remained close to 20 °C (Figure 5a).

The average stress at the contact interface between the billet and the tool reached approximately 800 MPa (Figure 5b), while the stress level in the carbide tool material reached 1132 MPa (Figure 5c).



*a)* *b)* *c)*

**Figure 5.** Distribution of strain and stress in the billet and tooling during the upsetting of A5056 aluminum alloy rivets *(interference fit = 0.1 mm), a - temperature distribution in the billet; b - equivalent stress distribution in the billet; c - equivalent stress distribution in the tooling*

Simultaneously, the maximum strain rate increases significantly from 0.09 $s^{-1}$ (on the testing machine) to 17.45 $s^{-1}$ (on an automatic cold forming press), which has a pronounced effect on increasing contact stresses in the tooling and consequently accelerates tool wear.

Due to the difficulties associated with conducting direct experiments on high-speed automatic cold forging machines, the adopted approach was to perform numerical simulations under conditions corresponding to the testing machine regime (forming speed of 0.033 mm/s), followed by experimental validation and comparison of the obtained results.

The average stress in the punch-die assembly at the boundary (see Figure 5c) varies with interference as follows: at 0 mm interference, the stress is 5 MPa; at 0.05 mm, it is −784 MPa; at 0.10 mm, it is −1132 MPa; at 0.15 mm, it is −1399 MPa; and at 0.20 mm, it is −1470 MPa (see Figure 4).

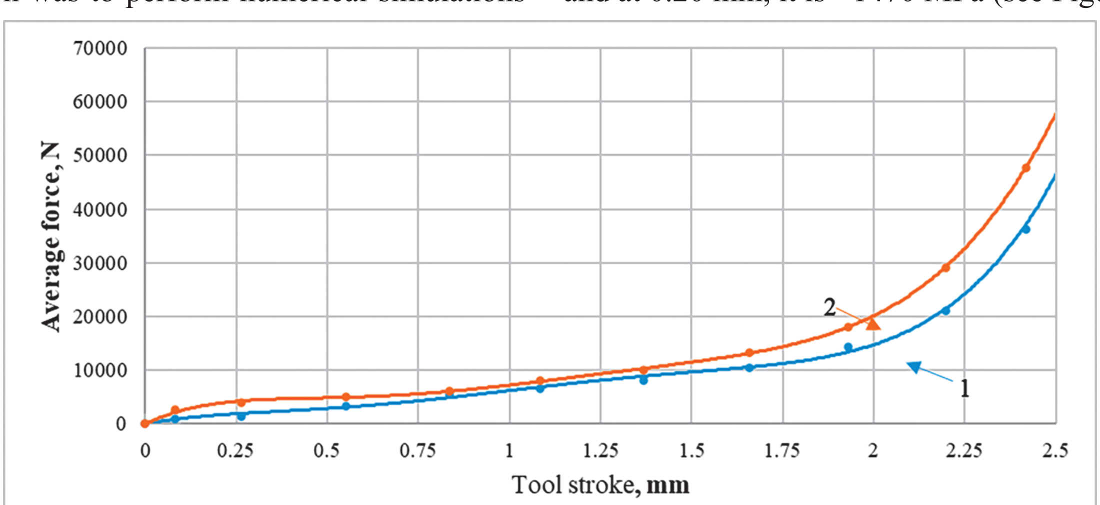



**Figure 6.** Relationship between riveting force and tool stroke for A5056 aluminum alloy rivets (1 - numerical simulation curve; 2 - experimental curve)

The comparison of process force parameters obtained from numerical simulation and experimental measurements showed that the deviation did not exceed 20% and remained within acceptable limits (Figure 6). This confirms the accuracy of the developed material model and demonstrates the applicability of QForm software for analyzing metal forming processes.

**Conclusions**

Through numerical simulation, it was determined that during the riveting of A5056 aluminum alloy on a testing machine, the average stress in the forming tool reached approximately 1132 MPa. The results indicate that when transitioning to strain rates characteristic of automatic cold forging presses, the workpiece temperature increases up to 140 °C, accompanied by a significant rise in strain rate. These effects must be considered in the design of industrial tooling systems.

Based on the stress field analysis, a relationship between the stress level in the punch-die system and the interference fit was established. To ensure substantial compressive stresses (784-1399 MPa) capable of compensating working loads, an optimal interference range of 0.10-0.15 mm is recommended.

The validation of the developed model, including the comparison of load-stroke curves and material strain hardening behavior, confirmed its accuracy. The proposed methodology enables the effective application of QForm software for solving practical problems in the design and optimization of cold forging tools.

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