Improving the quality of aircraft fasteners by transverse running with flat plates

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Abstract. For the strain hardening of aircraft fasteners, a surface plastic deformation method is proposed, based on running of blanks with smooth plates. The method allows processing parts that do not have center holes. Transverse running also eliminates the bending of the workpiece from the transverse loading forces action. Analytical dependences are obtained for determining the maximum possible contact area and relative compression for a transverse running. The quality of fasteners after transverse running with smooth plates provides the following favorable changes in the surface layer of metal: the formation of residual compressive stresses in the surface layers, a significant decrease in the initial roughness, an increase in the microhardness of the surface layer, the formation of a fine-grained structure, and the high accuracy of the machined parts diameter.

1. Introduction
Ensuring the safety and reliability of a modern aircraft is a complex task, and specialists from a number of scientific fields work on its solution. The main reason for the failure of the aircraft airframe is fatigue damage, 75-80% of which occur at the junctions of parts and assemblies [1]. Therefore, the nature of stresses and deformations in the fasteners’ contact area largely determines the life of the entire structure [2].

Today, mechanical connections using rivets and bolts are the most common in the airframes manufacture and constitute up to 90% of the total number of connections [3]. The covering of the aircraft’s airframe is a loaded structural member, perceiving up to 70-80% of the external loads acting on the airframe. In the aircraft design there are up to 200 thousand bolts. The fatigue resistance of compounds is determined by a number of factors, the most important of which are the effective stresses in the joint elements [4-6].

One of the ways to increase the machine parts fatigue strength is technological processing methods, which advantage is increasing endurance, in the absence of the necessary structural changes, which usually lead to an increase in the weight of the structure. The requirement to create a certain stress-strain state of the material at each power point has a significant impact on the technology for making joints. The formation of technological residual compressive stresses by plastic deformation not only leads to a decrease in stress concentration, but also slows down the fatigue cracks development [1].

In addition to bolted connections, studs are also used as fasteners in mechanical engineering. Such parts have a smooth cylindrical surface that senses contact pressure and axial tensile stresses. The performance of such parts largely depends on condition of the surface layer, which is formed as a result of mechanical machining. The existing methods of machining practically exhausted their potential for
improving the machine parts quality. The effective technological direction towards increasing the service life of machine parts, operating under alternating cyclic and re-static loads, is surface plastic deformation (SPD) treatment. The use of SPD in parts with structural stress concentrators is particularly effective [7].

The surface plastic deformation methods that have proven themselves to create a high-quality surface layer foil the low rigidity parts efficient processing. First of all, it is subject to the performance of the process and methods of fixing the workpiece before processing [8]. For this type parts hardening, a method is needed that does not require axial fastening and excludes bending from lateral loading.

Transverse rolling method on transverse running machines is known in the metal forming technology. The transverse running method is successfully used in metal forming. This is due to both its technological advantages and significant processing efficiency [9]. Flat-rolling mills have several advantages: ease of manufacture and low cost of flat tools, manufactured on universal milling and grinding machines; eliminating the need for a guiding tool; stable position of the part on the tool plane; high durability of flat tools (up to 500,000 parts); full process automation; high dimensional accuracy (0.01 ... 0.5 mm) of rolled parts. Compared, for example, with stamping, rolling provides an increase in productivity by 1.5–2 times, a reduction in the consumption of metal-roll by 10–30%; an increase in accuracy, a reduction in the labor intensity of subsequent operations, an increase in tool life (60–300 thousand pieces) and a significant reduction in its manufacture cost[10].

That is why transverse running method, as one of the types of SPD, is a promising direction [11]. Therefore, it became necessary to study this process in depth, to develop a general engineering methodology, which allows not only to predict the optimal choice of the processing modes main parameters, but also to carry out these parameters’ targeted management in the process of their practical implementation.

The purpose of this work is to determine the condition of gripping the workpiece, the stress state and the quality of the fasteners’ surface layer during with flat plates.

Scheme of the transverse running process. Consider the scheme of the process of hardening fasteners billet by transverse running with smooth plates. Figure 1 shows that the geometrical model of the running consists of the bottom rigidly fixed plate 3 and the upper moving plate 1 moving in the horizontal direction with the speed V. Between the plates placed blank 2 with a diameter of D.

![Figure 1. Scheme of the hardening fasteners billet process by transverse running with smooth plates](image)

The main transverse running parameters are the absolute compression and tool geometry. In the transverse running process, the tool has the appearance of a flat plate with a small angle of the inlet part α1 (Fig. 1). A small angle α2 in the output part of the tool serves to reduce the stress concentration when the part leaves the machining area. To implement this process of running it is necessary to determine its main parameters: the capture angle of the workpiece, absolute compression, stress state in the deformation zone, residual stresses after running.

2. Determination of gripping a blank with flat plates’ condition
To carry out the process of running the blank with flat plates, it is necessary to create certain conditions. Moreover, it is necessary to consider separately the conditions for the unsteady running process – for
the initial moment when the workpiece is only supplied to the plates (Fig. 2) and for the steady-state process, when the workpiece is already drawn into the plates (Fig. 3).

Consider the scheme of the workpiece capture by the flat plates (see. Fig. 2). In the lead-in part, the elevation angle $\alpha_1$ is the main geometrical parameter.

In the case of an unsteady running process at the moment when the workpiece contacts the plates, the latter will act on it in the form of $N$ forces directed normally to the shafts surface at the points where the workpiece contacts the plates $A$, and friction forces $F$ directed tangentially, as shown in fig. 2.

In order to identify the effect of the indicated forces $N$ and $F$ on the conditions for gripping the workpiece with plates, we project them onto the horizontal axis $XX$ (along the running direction) and onto the vertical axis $YY$.

To carry out the rolling process (axis $XX$), the horizontal force $F_x$ must be greater than the force $N_x$, then we have:

$$F \cdot \cos \alpha_1 > N \cdot \sin \alpha_1$$

$$\mu \cdot N \cdot \cos \alpha_1 > N \cdot \sin \alpha_1$$

$$\tan \alpha_1 < \mu$$

$$\alpha_1 < \arctan \mu$$

Figure 2. Scheme of the workpiece capture by the flat plates: 1 – movable plate, 2 - blank, 3 - fixed plate, 4 – stops

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where $\mu$ – coefficient of friction between the workpiece and the plates.

The value of the friction coefficient for a steel-steel pair during cold running is within the range from 0.03 to 0.15 [12-15]. According to the formula (1), we obtain the value of the angle $\alpha_1$, which is in the range from 2 ° to 8 °.

Next, we consider the scheme of transverse running with flat plates at the steady-state process, when the workpiece is already drawn into the space between the plates [16]. As Figure 3 demonstrates, the top plate movement direction is perpendicular to the rotation axis of the cylindrical body being rolled. The distance between the plates is less than the original diameter of the cylinder by $2y$ - this is the value of the absolute compression. The endeavors are used towards the workpiece in the direction of the central axis that are directed normally to the contact pad. The resultant of these efforts $P$ will be considered as applied in the middle of the segment corresponding to the zone where the workpiece contact the plates. Normal endeavors cause the friction forces to appear where the workpiece contact the plates, the which resultant is denoted by $F$. The friction forces $F$ are applied at the same points as the normal forces $P$ and are tangential to the contact area.
Figure 3. Endeavors scheme during transverse running in flat plates: 1 - movable plate, 2 - blank, 3 - fixed plate, rk - radius of the elastic core

In work [17] it is shown that, for the implementation of the running-in process, when the workpiece is already retracted by plates, the maximum value of the absolute reduction $\Delta H$ is calculated by the formula:

$$\Delta H = D - d = 2y = \frac{2\mu^2 D}{2\mu^2 + 1},$$

where $\mu$ – friction coefficient; $D$ – workpiece diameter.

Thus, the obtained value of the limiting capture angle $\alpha$ in the range of 2° - 8°. The maximum value of the absolute reduction depends on the friction coefficient and the workpiece diameter. To determine its optimal value, let us perform a simulation of the process of cylindrical billets transverse running with flat plates.

3. Simulation of the process of transverse running with flat plates

To determine the stress-strain state in the deformation zone and residual stresses in the straightened parts, a finite-element model in the form of a cylinder and two plates was built in the Ansys workbench program (Fig. 4). The following simulation parameters were adopted: a cylinder with a diameter of 10 mm, a length of 100 mm from steel St45 (yield strength $\sigma_t = 360$ MPa and an elastic modulus of $E = 2 \times 10^5$ MPa); working plates with dimensions of 5x110x110 mm are considered absolutely rigid.

Figure 4. Finite-element model of rolling cylindrical billets

Simulation parameters:
- finite element form – hexahedron, thickening of 7030 elements, 30620 knots;
- coefficient of friction between the workpiece and the plates $\mu = 0.15$;
boundary conditions: rigid fixation of the bottom plate;
by the formula (2), for a billet with a diameter of \( D = 10 \) mm, the maximum value of the absolute compression is \( \Delta H = 0.43 \) mm.

Processing modes: In the work, absolute reductions were used: \( \Delta H = 0.05; 0.07; 0.1; 0.15; 0.2; 0.25; 0.3; 0.4 \) mm. The top plate moves to the left by 62.83 mm (the workpiece is rotated 1 turn) and moves upward by 1 mm (unloading).

4. The stress state dynamics in the running process
The intensity of the working stresses arising in the deformation zone in the process of transverse running with flat plates is shown in Figure 5 (at \( \Delta H = 0.1 \) mm). The process of hardening the cylinder by transverse running with flat plates can be divided into 3 stages (see Fig. 5): A – lateral cylinder compression, B – lateral rolling for one cylinder revolution, C – unloading after lateral rolling.

![Figure 5](image)

**Figure 5.** The change in the intensity of operating stresses in the process of transverse running with flat plates

With the cylinder lateral contraction, the operating stresses increase to 435 MPa. At the transverse running stage, the working voltages remain constant, equal approximately to 440–450 MPa. During the final unloading, the working voltages monotonously decrease to the level of the intensity of residual stresses, which remain in the finished parts and are 282 MPa.
Figure 6. The dependence of the intensity of the working voltage on the absolute compression

The dependence of the intensity of operating stresses arising during transverse running on the absolute reduction $\Delta H$ is shown in Figure 6. In the deformation zone, the intensity of operating stresses increases rapidly with increasing $\Delta H$ to 0.07 mm, reaching 410 MPa, and then slightly raising with increasing $\Delta H$ to 0.25 mm. When the value of $\Delta H$ is less than 0.05 mm, the working stresses are less than the yield strength $\sigma_y$ (360 MPa) and therefore only elastic deformation is expected in this case. When the value of $\Delta H$ is greater than 0.25 mm, the working stresses are greater than the tensile strength $\sigma_t$ (600 MPa) and therefore, under such processing conditions, the material may be destroyed.

Thus, the optimal value of the absolute compression is in the range $\Delta H = 0.07$–0.25 mm.

5. Residual stresses after transverse running with flat plates

Due to the Ansys Workbench program [18, 19], the results of calculating the residual stresses after transverse rolling at an absolute reduction $\Delta H = 0.1$ mm were obtained (Fig. 7).

The stress intensity increases continuously from the center to the subsurface layers, and then decreases slightly on the cylinder surface (see Fig. 7.a). The radial residual stresses over the cylinder cross section (see Fig. 7.b) are tensile and monotonously increase from the surface of the cylinder to its center. The distribution of tangential and axial residual stresses is also alternating (see Fig. 7.c and d). For them, the maximum compressive stresses are observed at a certain depth from the periphery, and the maximum tensile stresses are observed in the cylinder central zone.
Figure 7. Fields of residual stress distribution over the section of the workpiece after transverse running with flat plates: a - intensity of residual stresses; b - radial residual stresses; в - tangential residual stresses; g - axial residual stresses

6. Assessment of fasteners quality after transverse running with flat plates

The experiments were performed on an experienced rolling machine. Cylindrical specimens with a diameter of 10 and a length of 100 mm from steel St45 were used as the investigated parts. The blanks are processed on a rolling machine with an absolute reduction $\Delta H = 0.1$ mm.

Evaluation of the rolled surface roughness. To measure the roughness and waviness parameters, a Taylor Hobson Form Talysurf i200 computer-controlled profilometer was used. The initial surface roughness of the parts was obtained after semi-turning, reaches the fifth class (Ra 2.5-5.0 microns). After transverse running, a surface with a roughness of $Ra = 0.27 \mu m$ was obtained. Thus, the roughness class increases, with an absolute reduction of 0.1 mm and reaches the eighth class.
Evaluation of the surface layer’s microstructure and microhardness. The microstructure was studied on a MET-2 microscope, which allows visually observing and photographing the microstructure of metals with an increase from 100 to 1000 times. Microstructure studies were carried out both in the cylinder’s axial zone and in the surface layer (Fig. 9). The cylinder core contains grains with a size of 20–90 μm, and on the surface zone, which is directly subjected to deformation, a finer-grained structure is observed with a grain size of 10–40 μm. The microstructure in this zone is characterized by the predominance of grains compressed in the radial direction and elongated in the axial direction. Grinding of the granular structure is a consequence of the metal grains crushing.

![Initial microprofile](image1)  
Initial microprofile  
Ra = 5.01 μm

![Microprofile when ΔH = 1mm](image2)  
Microprofile when ΔH = 1mm  
Ra = 0.27 μm

**Figure 8.** Surface profilograms before and after transverse running

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![Figure 9](image3)  
**Figure 9.** The sample microstructure after transverse running (an increase of 400 times): a) axial zone; b) surface area
To determine the distribution of microhardness in the radial direction, Vickers measurements were performed on a PMT-3 microhardness meter. Measurements were performed at a load of 200 g and a shutter speed of 10 s. The measurement of microhardness was made in 100 μm increments from the periphery to the center. The distribution of microhardness in the radial direction is shown in Fig. 10, which demonstrates that the microhardness reaches a maximum value on the surface and decreases when going to the center. The original part surface layer microhardness after turning is much smaller and varies from 210 to 216 HV$_{0.2}$. The microhardness of the hardened layer with transverse running reaches a value of 286 HV$_{0.2}$. From fig. 10, it is also possible to determine the depth of the hardened layer, which is 1.5 mm.

![Graph showing microhardness distribution](image)

**Figure 10.** The surface layer microhardness distribution

Thus, the results of theoretical and experimental studies have shown that the proposed method of finishing and strengthening the treatment by transverse running with flat plates can be recommended to improve the quality of fasteners such as bolts and studs. The high performance of the hardening process and the high quality of the surface layer should attract the attention of technologists and engineers for the implementation of the proposed technology in production.

7. **Conclusions**

1. A hardening scheme for cylindrical parts by transverse running with flat plates is proposed. The value of the limiting angle of capture $\alpha_1$ in the range of 2°-8° is obtained, the maximum value of absolute compression depends on the friction coefficient and the workpiece diameter, the optimal values of absolute reduction are in the range $\Delta H = 0.07$-$0.25$ mm.

2. With the help of the Ansys Workbench software package, the stress state is determined during transverse running with flat plates. The results of calculations showed that after transverse running with flat plates in the center of the workpiece transverse running, there is a stress state of all-round tension, and a compression stress state is formed in the workpiece’s surface layers.

3. Experimental studies to assess the fasteners quality after transverse running with flat plates provide the following favorable changes in the surface layer of the metal: a significant decrease in the initial roughness, an increase in the microhardness of the surface layer, the formation of a fine-grained structure, ensuring high precision of the machined part.

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