Research of Residual Stress After Deformation and Annealing of a Titanium Alloy Ti-5Al-5Mo-5V-1Cr-1Fe Billets

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Abstract. Research of opening angle changes in bent billets of Ti-5Al-5Mo-5V-1Cr-1Fe alloy after bending and annealing at temperature 800°C for 1, 2, 3, 4, 5 hours has been madeto improve the accuracy of the titanium parts manufacture. The change of surface residual micro- and macrostrains via X-ray analysis was found depending on the duration of annealing. It was found that the value of the opening angle between the legs bent billets is defined by the influence of the level of residual microstress. To maintain the geometry of the bent billets it is recommended to anneal them at a temperature of 800°C for 2 hours.

1. Introduction

Residual stress appears in the formed products during manufacturing operations and material processing, such as molding, welding, forging, rolling, stamping, machining and a heat treatment. The occurrence of residual stress in most cases is caused by the following factors: the heterogeneity of a plastic deformation in cross sections of details, uneven temperature distribution in terms of products, irregularity of processes of phase, the structural and physic-chemical transformations in the product material [1].

Typically, residual stresses play a negative role. It is found that the residual stresses decrease the strength of products under varying cycle loads, affect friction wear, stimulates corrosion processes [2 - 4]. There are enough examples of destruction caused by significant technological residual stresses [5 - 9].

At present, there are many methods for measurement of residual stress based on partial damage of the measured product (drilling holes and measuring surface deformation with using special sensors). The most accurate and reliable method for determining residual stresses on the cylindrical surface has been proposed by Sachs. It is based on the product bore in layers of desired value and subsequent measurement of the axial and radial deformation. Further, according to the formulas of the Elasticity Theory, a calculation of the principal stresses in the cylinder is implemented. However, this method is very complex, time-consuming and cannot be implemented for thin workpieces and products used in the construction of aircraft engines.

X-ray methods [10] for the study of residual stresses on the surface of parts of any shape that can be used to analyze the structure of thin-walled objects. They allow studying macro-, micro stresses on a 0.5 mm depth. Therefore the X-ray method is available for a thin body part.

In the manufacture of parts and components made of titanium alloys all kinds of machined castings and forgings are used: turning, milling, drilling, grinding, and polishing. From the one hand, these techniques provide a high accuracy of products, thereby reducing the vibration and noise in aircraft engine parts [11-12]. On the other hand, when the decompensation occurs during machining and relaxation of internal and surface residual stresses appears, leading to a distortion of workpieces configuration.
An important feature of the machining of titanium alloys is a need to ensure the resource, especially fatigue, features that are to a great extent caused by the quality of the surface layer formed after cutting treatment.

In mechanical treatment of cutting, when the tool removes a part of the workpiece surface (processing allowance), the material undergoes a significant structure changes and redistribution of internal stresses. The cutting tool is also the source of the stress, because tool heats and deforms a material in a treatment zone. This residual macrostress may have a significant impact on the quality of the finished part, causing warping of the workpiece or cracks on the materialsurface. The ability of residual stresses is more dangerous in the reason stress relaxation occur over time - when processing is already finished, the mechanism's detail suddenly begins to wear out quickly due to the exceeding of size over limits.

Alloy Ti-5Al-5Mo-5V-1Cr-1Fe is intended for highly loaded structures and components, continuously operating at temperatures of 350 - 400 °C. Force parts, parts of management system, fasteners of force bolts are produced of it. The process of manufacturing of parts made of Ti-5Al-5Mo-5V-1Cr-1Fe includes stockpiling manufacturing (casting, forging), annealing, machining [13-14].

The aim of this research was to investigate the change in configuration and level of surface macro- and microstress in flat workpieces of titanium alloy Ti-5Al-5Mo-5V-1Cr-1Fe after bending and heating.

2. Materials and Methods

Samples of size 2x10x30 mm were cut from a commerce rod (AMTU 451-67) by spark erosion, which ensures the structure and properties savingas in the original piece. The chemical composition of the alloy in accordance with Russian Standard OST 90013-81 is presented in Table 1.

| Fe | C  | Si | Cr | Mo | V  | N  | Ti  | Al  | Zr | O  | H  |
|----|----|----|----|----|----|----|-----|-----|----|----|----|
| 0.5| Up to | Up to | 0.5 - | 4 | 4 | Up to | 78.485 | 4.4 | Up to | Up to | Up to |
| 1.5| 0.1 | 0.15 | 2 | 5.5 | 5.5 | 0.05 | 86.6 | 5.9 | 0.3 | 0.2 | 0.015 |

After cutting samples were subjected to bending deformation in a tool die with an apex angle of 90 deg. and fillet radius of 10 mm (die scheme is shown in Figure 1). After bending, the samples were annealed in laboratory furnace at 800°C for 1, 2, 3, 4 and 5 hours.

![Figure 1. Scheme of the instrumental die.](image)
Residual macro- and microstresses were studied using X-ray diffraction analysis for the convex and concave sides of the samples using focusing by Bragg - Brentano. According to [15], the residual stress was considered for the plane (211), a middle plane since secondary interference lines have the minimum error.

3. Results
According to the calculation results, we noted residual macro and micro stresses curves depending on annealing time of bent samples (Figure 3 and 4).

Figure 3 analysis shows that annealing duration less two hours reduces macrostresses nearly 5 times. Longer duration causes a sharp increase in macrostresses almost 10 times. Then with increase of annealing time up to five hours macrostresses were reduced by 20%. It should be noted that annealing does not change macrostresses kind - they remain positive (or stretching). Microstresses have negative values, indicating their compressive origin. They decrease in modulus with increasing of annealing time up to three hours at about 11 times, then decrease in absolute value to 64%. Further, with increase of annealing time microstresses also increase.
Figure 4 shows that annealing up to two hours reduces the macrostresses approximately 7.5 times compared to deformed state. Longer duration causes a sharp increase in the macrostresses almost 11 times. Micro stress decrease in modulus with increasing annealing time up to three hours to approximately 73%, then reduced modulo 15 times.

Comparison of Figures 3 and 4 shows that the macro- and microstress are higher in the compression zone than in the stretch zone. Macrostresses reducing at the initial stages of annealing at period up to 2 hours can be explained by a decrease in defects in the structure due to polygonise processes, emerging high angle boundaries and division of separate grains into subgrains. Microstresses that are balanced within a few grains, increase due to the emergence of the dislocation walls. Start of a recrystallization process is accompanied by the appearing and growth of new grains with a minimum distortion, which is accompanied by a decrease in microstrain. Perhaps, in this case, the driving force of grain boundaries is the residual microtension. Increase of macro stresses during annealing for more than three hours can be explained by the appearance of fine-grained structure as a result of the primary recrystallization, the length of grain boundaries increases, which causes an increase in residual macrostresses.

Figure 5 shows that the angle after annealing increases. Thus, increasing the annealing time leads to the opening of angle between the bent workpiece shelves. But this change is nonmonotonic, as in the case for a change in the residual macro- and microstresses. It is possible that the change of geometry samples affects the driving force depending on the level of macro- and microstresses.

To determine the influence of the residual macro and micro stresses on the change of the opening angle between the legs of bent billets diagrams were constructed. Since stress is symmetrical in compressive and strain
zones relatively neutral layer, angle change curves were constructed according the middle arithmetic values of residual stress for strain and compressive zones and shown in Figure 6 and 7.

![Image](image_url)

**Figure 6.** Dependence of the relative change in the angle of opening of the average value of macrostress.

Figure 6 shows that the increase in the average value of macro stress from 500 MPa to 4500 MPa increases the opening angle more than 2 times. But a clear correlation between the change of the macrostresses and the angle of opening billets between shelves is not observed.

![Image](image_url)

**Figure 7.** Dependence of the relative change in the angle of opening of the average value of microstress.

Figure 7 shows that an increase in the average value of microstresses from 500 to 3000 MPa results in an increase of more than 8 times in the relative change of angle. At the same time there is a steady monotonic dependence of the relative change of the opening angle between the legs of the micro stress values.

4. **Conclusions**

1. It was established that during bending samples of alloy Ti-5Al-5Mo-5V-1Cr-1Fe macrostresses are formed in the surface layers, which have a positive sign or stretching character, and microtension have a negative contractive character. Changes in the macro and micro stress on the outer and inner sides of the bent workpieces have similar behavior patterns, but their level of compression zone exceeds similar values measured in the stretch zone.

2. An increase in geometry change is observed with the increase of macro- and microstress. The driving force of recrystallization processes in the bent billets after heating at 800°C is the residual micro stress.
3. For minimal warpage, shape preserving of cold-deformed bent workpieces during subsequent heating as a result of thermal or mechanical treatment they must be subjected to annealing at a temperature of 800°C for 2 hours. Thus minimum values of macro stresses and opening angle between the legs of bent billets are achieved.

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