Stress-strain state and structure of pure copper and Grade 4 titanium after free bending

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Abstract. This paper investigates the stress-strain state and the features of structural transformation in materials with different types of crystalline lattices in the process of deformation by free bending of axis-symmetrical billets. As the materials for the study, we selected oxygen-free Mo0B Cu and Grade 4 CP Ti. Using mathematical modeling, we study the stress-strain state of the samples from the selected materials in the process of bending via different routes. We study the structure in the mesoscale and determine the features of structural transformation. It is found that in the process of bending of Cu, a refined surface layer with a thickness of 20-30 μm and a cell size of ≈1 μm forms already after 1 processing cycle. In the process of bending of Ti, twinning occurs in peripheral regions, and the efficiency of twinning via route С is higher than that via route А. The most efficient, in terms of strengthening, processing routes of bending are determined.

1. Introduction

Recently, under active development are the methods that increase the strength of materials while preserving high ductility values due to the formation of a gradient-type structure in products [1]. For instance, in [2-4] it was shown that the yield stress of Cu can be increased, while preserving the initial ductility value, due to the formation of a gradient structure. Such an increase in ductility is related to the delocalization of strain in the sample volume and the redistribution of stresses. In addition, the strengthening of the surface layer also leads to an increase of the material’s fatigue properties. This is conditioned by an increase in the crack resistance of the surface due to an increase in the strength and a decrease in surface roughness [2].

Among the known methods for producing products or semi-products with a gradient-type structure are various types of local plastic treatment (smoothing, grit-blasting, etc.) and bulk deformation methods, e.g., free and constrained torsion or bending of axis-symmetrical billets, normally having a round section. The present paper examines the features of the free bending process of a rod. The advantages of this method are technological effectiveness and the simplicity of equipment, a relatively small change in the cross section of the billet during the processing, the absence of tribological problems, e.g., during continuous bending around rotating rollers, and low force expenditures. It is obvious that in the process of bending a gradient of accumulated strain distribution is observed, with the maximum values in the surface area and the minimum values in the centre. From the scientific perspective, it is
interesting to study the effect of the stress-strain state, type of crystalline lattice, processing parameters on the features of structural transformation for such alternating deformation processing. The main focus of the present work is the study of the stress-strain state during bending and the effect of the type of crystalline lattice on the character of the initial structure’s transformation. As the materials for the study, we selected oxygen-free М00B Cu (FCC) and Grade 4 commercially pure (CP) Ti (HCP).

2. Material and experimental procedures

As the materials for the study, we selected oxygen-free М00B Cu (FCC) and Grade 4 commercially pure (CP) Ti (HCP). The initial coarse-grained state of Cu was produced by holding the samples at 600 °C for 1 hour followed by cooling in air. For Ti, the initial state was produced by holding at 700 °C for 3 hours followed by cooling in air. The diameter of the samples was 5 mm, length 125 mm.

The processing by free bending was performed using a special experimental facility, with a bending radius of 15 mm. The processing was conducted via routes A and C. Route A implies bending a sample by 90°, straightening it and repeating the bending operation. Route C implies bending a sample by 90°, straightening it and bending it in the opposite direction (-90°), then returning it in the initial position. In the process of the experiment, 1 and 4 processing cycles were implemented. The processing was conducted at room temperature equal to 20 °C.

The stress-strain state was studied using the finite-element computer simulation in the Deform-3D software package.

The billet model had the same sizes as the physical billet, i.e. diameter 5 mm, length 125 mm. The models of billet materials were selected from the Deform 3D material library. Oxygen-free Cu – C10100 Machining, CP Ti – Ti-Type-1, cold.

The generated finite-element mesh consisted of tetrahedra amounting to 15 000 pcs. The option of compensation of the billet model volume was activated. The initial billet was a plastic body, and the tool was an absolutely rigid body. The tool models were not divided into the finite-element mesh.

The bending rate was taken as constant and equal to 1 rad/s. The temperature of the billet and tool была taken as room temperature, 20 °C. The simulation was performed without taking into account the increment in the billet temperature from the thermal effect of plastic deformation. The Siebel friction factor was $f = 0.2$. For the contact surfaces of the die-set, the condition of non-permeability was set.

To analyze the stress-strain state, we studied the mean stresses that were calculated according to the following formula [5]:

$$
\sigma_{\text{mean}} = \frac{1}{3} \cdot (\sigma_1 + \sigma_2 + \sigma_3),
$$

where $\sigma_1$, $\sigma_2$, $\sigma_3$ are the principal stresses. The mean stresses in the considered point of a deformed body determine the rigidity of the stress state pattern.

Metallographic studies were performed in the longitudinal section of a sample in the central and peripheral regions by SEM (JEOL JSM-6490LV) in the SEI regime. Microhardness studies were performed using a Micromet 5101 microhardness tester in the longitudinal section of a sample from the outer radius at the last bend to the interior radius.

3. Results

3.1. Finite-element computer simulation

On the basis of the computer simulation results, we investigated the stress-strain state of the samples subjected to stationary free bending: 1 processing cycle, and 4 processing cycles for each route, A and C. The figures given below show the field and diagrams of the distribution of accumulated strain and mean stresses in the longitudinal section of the samples.

Analysis of the obtained patterns of the strain state reveals that in the process of bending, irrespective of the route and number of processing cycles (figures 1-3), the accumulated strain distribution in the sample has a non-homogeneous character, with large values in the peripheral regions of the billet and
smaller values in the center. The diagrams of accumulated strain distribution have a non-symmetrical parabolic view, which indicates a gradient strain distribution in the section. The non-symmetrical strain distribution shows that at the initially outer radius of bending (the region of compression after straightening) much higher strain values are accumulated than at the interior radius of bending (the region of tension after straightening).

One processing cycle leads to producing approximately the same accumulated strain in both the Cu samples and the Ti samples.

Further deformation by bending promotes strain accumulation. Route C (figure 3) produces a more homogeneous and symmetrical state than route A (figure 2). However, route A leads to a proportional growth in accumulated strain (proportionately to 1 cycle), unlike route C where the growth of accumulated strain after the first processing cycle decreases considerably, and after 4 cycles the maximum values reach only $e=1.2\ldots1.4$ instead of the expected $e=1.8\ldots2.0$.

The stress state in all the cases is very non-homogeneous (figure 4). With increasing number of processing cycles and, correspondingly, growing strengthening, the values of mean stresses increase. For example, in the Ti sample in the studied region for 1 bending cycle the tensile stresses reach 80 MPa, the compressive stresses reach 380 MPa, and for further processing for 4 cycles via route C the tensile stresses reach 260 MPa, the compressive stresses reach 480 MPa. It can be noted that when the direction of bending is changed, cyclic changes in the mean stresses are observed. For example, in the initially interior layer of the billet, first compressive stresses are observed during bending, then, when the direction of bending is reverse, tensile stresses are observed, and in the outer layer vice versa.

**Figure 1.** Accumulated strain distribution in the longitudinal section of the sample subjected to 1 cycle of bending: a) from M00B Cu; b) from Grade 4 CP Ti.

**Figure 2.** Accumulated strain distribution in the longitudinal section of the sample subjected to 4 cycles of bending via route A: a) from M00B Cu; b) from Grade 4 CP Ti.
Figure 3. Accumulated strain distribution in the accumulated strain distribution subjected to 4 cycles of bending via route С: a) from М00B Cu; b) from Grade 4 CP Ti.

Figure 4. Mean stresses distribution in the longitudinal section of the sample subjected to 4 cycles of bending via route С: a) from М00B Cu; b) from Grade 4 CP Ti.

3.2. Analysis of the structure and microhardness

In the initial state oxygen-free Cu is characterized by a coarse-grained structure with a mean grain size of 40±5 μm. Multiple growth twins are observed in grain interiors. After 1 cycle of processing by bending, a surface deformed layer with a thickness of 20-30 μm is formed. The layer’s structure represents elongated cells with a mean size of 1±0.2 μm and the elongation factor 1:2. In the rest of the volume, a coarse-grained structure with a grain size of 35±4 μm is observed. An increase in the number of bending cycles up to 4 does not lead to an increase in the thickness of the deformed layer, and the grain size in the central region of the sample is preserved as 34±4 μm, irrespective of the route (figure 5). Growth twins are preserved in the grain interiors.

Ti in the initial state is characterized by a coarse-grained structure with equiaxed grains, the mean grain size being 8.3±0.6 μm. As revealed by structural studies, 1 cycles of processing by free bending leads to an insignificant structural transformation. The structure is homogeneous across the section, and the mean grain size is 7.8±0.6 μm. When the number of cycles via route A is increased to 4, the coarse-grained equiaxed type of structure is retained (the mean grain size is 8.2±0.6 μm), but in some grains in the peripheral region twins of deformation origin with a thickness of 0.8-1.0 μm can be seen (figure 5). For the processing by bending for 4 cycles via route С, the character of structure corresponds to the structure after 4 bending cycles via route A.

The microhardness values across the section of Cu and Ti samples processed by bending indicate a gradient strain distribution. The minimum microhardness values are found in the central region. The microhardness in the peripheral region (figure 6, point 0) subjected to tensile stresses is 1.2 times lower than the microhardness value in the compression region (figure 6, point 5). In both oxygen-free Cu and Ti considerable strengthening takes place already after 1 bending cycle. The maximum microhardness values are reached after 4 cycles and amount to 1090±50 MPa for Cu and 3380±60 MPa for Ti.
Figure 5. Structure of pure Cu and Grade 4 Ti: a) pure Cu in the initial state, b) Grade 4 Ti in the initial state, c) pure Cu after 1 bend, d) Grade 4 Ti after 1 bend, e) pure Cu after 4 bends via route A, f) Grade 4 Ti after 4 bends via route A, g) pure Cu after 4 bends via route C, h) Grade 4 Ti after 4 bends via route C.

Figure 6. Microhardness across the section of the samples of pure Cu (a) and Ti Grade 4 (b).
Thus, in the process of bending in oxygen-free Cu we observe a transformation of the surface layer. A gradient type of microhardness distribution is observed, the values grow from the center to the periphery (figure 3), which correlates with the results for the stress-strain state obtained by simulation. The maximum microhardness value is reached in the periphery of the sample subjected to compressive stresses at 4 bending cycles via route A. In this region, the maximum strain \( \varepsilon = 2 \) is achieved. After 4 bending cycles the accumulated strain distribution in the peripheral areas becomes more symmetrical.

On the basis of the simulation results, for Ti we also observe a gradient distribution of strain and stresses, growing from the center to the periphery. Twins are observed in the peripheral region. The calculation of the number of twins after 4 cycles demonstrates that for route A the density of twins is \( 6 \cdot 10^4 \mu m^2 \), and for route C the density of twins is 2.3 times higher \( 14 \cdot 10^4 \mu m^2 \). Thus, twinning in Ti under alternating deformation occurs more actively. It should also be noted that microhardness measurements revealed that in Ti in the peripheral area strain localization takes place in the material’s volume at a distance of up to 1/4 diameter from the sample edge.

4. Conclusions
1. Using computer simulation, it was found that after processing by bending a gradient field of accumulated strain is formed, irrespective of the route, number of cycles and used material. The maximum strain values are observed in the surface layers of the billet, and the minimum values are found in the central region. However, one processing cycle leads to a non-symmetrical distribution of accumulated strain. The use of routes A and C enables achieving a more symmetrical distribution of accumulated strain. The data for the stress-strain state obtained by mathematical modeling correlate with the data obtained by structural studies.
2. In the process of bending of Cu, already after 1 cycle a surface refined layer is formed, with a thickness of 20-30 \( \mu m \) and a cell size of \( \approx 1 \mu m \). With increasing number of bends, the layer thickness and the cell size do not change. Microhardness distribution across the section has a gradient character, the maximum value is reached in the peripheral region and amounts to 1090±50 MPa.
3. In the process of bending of Ti, twins of deformation origin emerge in the peripheral regions. The microhardness variation across the section has a gradient character. The maximum strengthening takes place after 4 (routes A and C) cycles of bending and amounts to 3380±60 MPa. Twinning in Ti occurs more actively under alternating deformation.
4. In the process of bending of Grade 4 Ti, strain localization takes at a distance of 1/4 diameter of the sample from the surface.

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