Study of the processing of long-length billets by continuous free bending

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Abstract. This paper investigates the features of deformation processing by continuous free bending in rollers, aimed at enhancing the mechanical properties of long-length metallic billets without any change in their cross section. As the material for the investigation, we selected a chromium-zirconium bronze for electrical engineering applications, used, for example, for the production of contact wires that require high mechanical characteristics. Computer simulation reveals that during the processing by continuous free bending, a gradient field of accumulated strain is formed, with maximum values in the peripheral region and with minimum values in the center of the billet. It is found that during bending, by the 6th cycle the peripheral layers of the billet accumulate a strain of $e \sim 2$, and the damage reaches a value of $\sim 1$. In the process of verification by means of a physical experiment, cracks emerge on the billet surface during the 6th cycle, confirming the simulation data. Structural analysis shows that during multi-cycle processing by this method, a gradient type of structure is formed. An important advantage of the processing by continuous free bending is the enhancement of the mechanical properties of long-length samples without any reduction in the cross-sectional area: e.g., after 4 processing cycles the ultimate tensile strength increased from 250±20 to 380±20 MPa, and the variation of the cross-sectional area was $\sim 5$-7%. The obtained results are in agreement with some principles of severe plastic deformation processing.

1. Introduction
The results of studies of the severe plastic deformation (SPD) techniques demonstrate the efficiency of their application for the enhancement of mechanical properties [1-3], however, attention should be paid to the difficulty of implementation of SPD technologies, primarily related to the insufficient technological efficiency of these processes. For instance, the techniques based on equal-channel angular pressing (ECAP) involve some tribological problems that need to be solved. Conventional methods of deformation processing, such as rolling and drawing, enable enhancing the mechanical properties of metallic materials, but at the same time reduce significantly the cross-sectional area.

2. Method description
An alternative to the above-mentioned techniques could be deformation by bending that implements shear. Pioneer studies of bending as a deformation procedure demonstrate the positive role of this approach for the refinement of the initial structure in sheet billets [4-6].
In the present study, we investigated the deformation processing of long-length rod-shaped billets by continuous free bending technique (figure 1) in round rotating rollers with open passes, without any lubricants. This design enables a visual inspection of the process.

Figure 1. Principle of continuous free bending.

3. Material and experimental procedures
As the material for the study, we selected the low-alloyed alloy Cu-1Cr-0.08Zr (wt.%). This alloy is used for the manufacture of electrodes for resistance spot welding and resistance seam welding, railway contact wires, as well as other parts that require a combination of high electrical conductivity and high hot strength [7-9]. In the study, we used rod-shaped samples with a diameter of 10 mm and a length of 600 mm. In the process of research using the Deform-3D software system, we performed the finite-element computer simulation to study the strain state and the thermal effect of deformation. Further, we conducted a physical experiment – the samples were subjected to thermomechanical treatment comprising two stages:
- at the first stage, a high-temperature treatment – exposure for 1 hour at a temperature of 1000 °C, followed by water quenching;
- at the second stage, the samples were subjected to deformation by continuous free bending in rollers. The number of processing cycles was 1, 4 and 6 (until the emergence of cracks on the surface of a sample). After each cycle, the billet was rotated by 90°. The processing temperature was room temperature, and no lubricants were used.

After the processing of the samples, we performed mechanical tensile tests and structural analysis using light and scanning electron microscopy.

4. Results
4.1. Computer simulation of the continuous free bending process
At this stage of research, the main attention was given to the process of strain and damage accumulation (figure 2).

It follows from the analysis of the accumulated strain distribution fields that in the process of bending a gradient strain field is formed: higher strains are observed at the periphery, while lower strains are found in the central region of the deformed billets (figure 2 a, b). Correspondingly, both the structural changes (refinement) and strengthening in the surface peripheral regions will proceed more actively than in the central region of the billets. The accumulated strain after 1 cycle varies from 0.2 in the central region to 0.5 at the surface. To ensure a symmetrical strain distribution, it is necessary to implement at least 4 processing cycles, resulting in strains varying from e=0.75 in the center to e=1.8 at the surface of the billet. After 6 cycles, the values of accumulated strain are e=1.7-2.0 at the periphery and e=0.8-1.0 in the central region (figure 2 a, b). It should be noted that for products experiencing bending and wear during operation the enhanced strength of surface layers provides an increase in operational life.
The results of our study also show that by the 6th processing cycle, the level of damage reaches \( \sim 1 \), which indicates that the technological plasticity is exhausted. The increment in damage in one processing cycle is \( \sim 0.2 \). This result is confirmed by the physical experiment: after the 6th cycle, cracks with a depth of about 200-300 \( \mu \text{m} \) emerge on the billet surface.

![Image](image_url)

Figure 2. Billet after 6 processing cycles: accumulated strain distribution fields (cross section, a, b) and accumulated damage (surface, c, d).

4.2. Microstructural analysis and mechanical properties

The microstructure in the sample after 6 cycles of continuous free bending is shown in figure 3. As a result of the processing, a gradient type of structure is formed. In the central region of the sample, coarse grains with growth twins are observed, the mean grain size is 42±3 \( \mu \text{m} \). In the near-surface layer, grains close to equiaxed ones are observed, with a mean size of 15.0±0.8 \( \mu \text{m} \). In the surface layer, a refined structure with a mean grain size of 7.1±0.5 \( \mu \text{m} \) is found. This distribution corresponds to the results of the computer simulation of the strain state. In the bulk of the billet, large particles of elongated second-phase particles with an average cross size of 0.90 ± 0.07 \( \mu \text{m} \) are observed. Mechanical fragmentation of particles is not observed.

![Image](image_url)

Figure 3. Microstructure in the sample after 6 cycles of continuous free bending (longitudinal section, SEM): a – central region, b – near-surface layer, c – surface layer.
After 4 processing cycles, in the Cu-1Cr-0.08Zr alloy, the ultimate tensile strength increased from 250±20 MPa in the initial as-quenched state to 380±20 MPa in the deformed state.

5. Conclusions
The following conclusions can be drawn from the conducted study:
1. The computer study of the stress-strain state in the process of continuous free bending in rollers shows that:
   - During bending, a gradient strain field is formed, irrespective of the number of processing cycles. Higher strains are accumulated in the peripheral region. For example, after 6 processing cycles, the difference in the values of accumulated strain in the central and peripheral regions reaches ~1, the maximum value being e=2.
   - The increment of the accumulated strain in one processing cycle is up to 0.2 in the central region and up to 0.5 on the surface, and the increment values decrease with increasing number of cycles.
   - The damage increment in one processing cycle is ~0.2. By the 6th processing cycle, the damage level reaches values exceeding 1, which indicates that the technological plasticity of the peripheral regions of the billet has been exhausted.
2. Verification of the computer simulation of continuous free bending in rollers by means of a physical experiment shows that:
   - A gradient type of structure is formed in the sample, with a mean grain size of 42±3 µm in the central region, 15.0±0.8 µm in the near-surface layer, 7.1±0.5 µm in the surface layer.
   - The processing by continuous free bending in rollers ensures the enhancement of mechanical properties of long-length samples without a considerable reduction in the cross-sectional area: after 4 cycles of processing of the Cu-1Cr-0.08Zr alloy, its ultimate tensile strength increased from 250±20 to 380±20 MPa, and the change in the cross-sectional area was only ~5-7%.

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