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# Formation of the Mechanical Properties of Copper Strips during Alternating Elastoplastic Bending

**A. E. Shelest[a], *, V. S. Yusupov[a], M. M. Perkas[a], E. N. Sheftel'[a],**
**K. E. Akopyan[a], and V. V. Prosvirnin[a]**

*[a] Baikov Institute of Metallurgy and Materials Science, Russian Academy of Sciences,*
*Leninskii pr. 49, Moscow, 119991 Russia*
**e-mail: shelest99@mail.ru*

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**Abstract**—A model is developed to determine the geometric and deformation characteristics of copper strips during alternating elastoplastic bending with a decreasing radius of curvature. This model is experimentally shown to satisfactorily correspond to the real conditions of deformation of commercial-purity copper strips on a roll leveling machine. The maximum effect of this processing is found to consist in a significant (by three–five times) increase in the yield strength of copper strips in only one pass. The developed model can be used to find the boundary of alternating deformation at which the entire cross section of the strip passes into the elastic deformation zone.

*Keywords:* elastoplastic deformation, alternating bending, decreasing radius of curvature, cumulative deformation, commercial-purity copper, leveler, tensile properties

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## INTRODUCTION

When sheets are flattened on roll leveling machine, strip is subjected to alternating bending, where the relative elongation (Fig. 1, $\varepsilon_{\text{out}}$ for outer fiber) and shortening ($\varepsilon_{\text{in}}$ for inner fiber) strains are determined from the relations (%) [1]

$$\varepsilon_{\text{out}} = 100H/2R_{\text{cur}}, \quad \varepsilon_{\text{in}} = -100H/2R_{\text{cur}}, \tag{1}$$

where $H$ is the strip thickness and $R_{\text{cur}}$ is the radius of curvature of the neutral plane passing through the center of the strip thickness. The intensities of the principal true elongation and shortening strains for outer and inner fibers are

$$e_{i_{\text{out}}} = \ln\frac{R_{\text{cur}} + 0.5H}{R_{\text{cur}}}, \qquad e_{i_{\text{in}}} = \ln\frac{R_{\text{cur}} - 0.5H}{R_{\text{cur}}}, \tag{2}$$

respectively.

In the case of bending during the point contact of a sheet with a roll, the radius of curvature of the neutral plane of the strip is

$$R_{\text{cur}} = \frac{\sqrt{(0.5L)^2 + (H-G)^2}}{4\cos\{\arctan[L/2(H-G)]\}}, \tag{3}$$

where $L$ is the distance between the roll axes and $G$ is the distance between the planes that are tangential to the generatrices of the upper and lower roll rows at the bending sites (overlap at $G < 0$, gap at $G \geq 0$).

The absolute strain $\Delta l$ diagram across strip thickness $H$ is straight line $de$, which passes through point 0 in the neutral line in bending the strip (see Fig. 1). The base of the diagram is segment $cf$, which is part of the abscissa axis, and the ordinate axis is the tangential to the neutral line at point 0. It is important that the strains in bending can be elastic r plastic depending on the stresses induced by applied bending moments $M_{\text{ben}}$ or, in other words, the radius of curvature of the neutral line. It is reasonable to choose relative strain $\varepsilon_{0.2}$ (segment $ab$ in Fig. 1) as a conventional boundary between the elastic and plastic strains. According to the existing standards, this strain characterizes yield strength $\sigma_{0.2}$ in tensile tests [2]. From the similarity of triangles $0ab$ and $0cd$, we have $0a/0c = ab/cd$ and $0a = ab \times 0c/cd$. The elastically deformed layer thickness is $\Delta = 20a$ and $H = 20c$; therefore, we have

$$\Delta = \varepsilon_{0.2}H/\varepsilon_{\text{out}}. \tag{4}$$

Thus, the metal undergoes cold working due to plastic deformation only in sections $ac$ and $gf$ of the cross section of the strip.

At small argument $x$, the logarithmic function can be roughly determined as $\ln(1 + x) \approx x$. Then, in the case of estimating the true principal strain intensity for a linear state of stress (bending and tension schemes), we have $e_i = \ln(l/l_0)$, where $l$ and $l_0$ are the current and

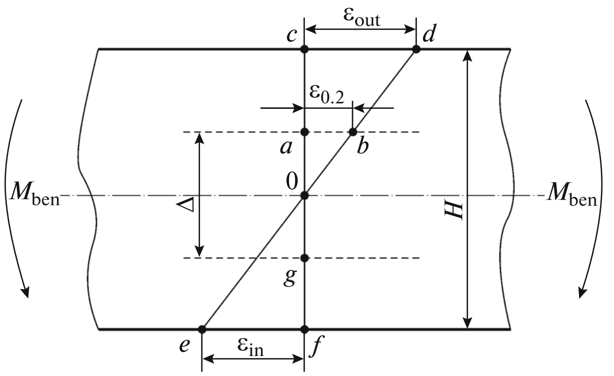

**Fig. 1.** Scheme for determining the elastoplastic layer thickness in bending a strip.

initial lengths of the chosen fiber or segment, respectively, and the last relation can be rewritten as $e_i = \ln(l/l_0) = \ln(1 + x)$, where $1 + x = l/l_0$. Here, we have $x = l/l_0 - 1 = (l - l_0)/l_0 = \Delta l/l_0$; i.e.,

$$e_i = \ln(1 + \Delta l/l_0) = \Delta l/l_0, \tag{5}$$

where $\Delta l$ is the absolute elongation of the chosen fiber or segment.

As follows from Eq. (5), the distribution of true principal strain intensity $e_i$ across thickness *ac* of the plastically deformed layer repeats the $\Delta l$ distribution, i.e., along line *bd*. Thus, the average true principal strain intensity is $e_{i_{\text{av}}} = 0.5(e_{i_{\text{out}}} + e_{i_{0.2}})$, where $e_{i_{\text{out}}}$ and $e_{i_{0.2}}$ are the true principal strain intensities in the outer fiber and at the boundary with the elastically deformed central layer of the strip. $e_{i_{0.2}}$ is specified by linear strain of 0.2%, which corresponds to yield strength $\sigma_{0.2}$. If this strain is neglected because of its smallness, the average true principal strain intensity can be estimated by the relation

$$e_{i_{\text{av}}} = 0.5 e_{i_{\text{out}}}. \tag{6}$$

Similar relations are valid for analysis of the deformation of the lower half of the strip, the fibers of which undergo shortening upon bending (see Fig. 1). The action of this deformation on the properties of the strip is identical to the hardening effect in elongation [3]. Therefore, the cumulative true principal strain intensity in the cross section of the strip during its passage through a mangle is

$$e_{i_{\Sigma}} = \sum_{j=1}^{k} e_{ij_{\text{av}}}, \tag{7}$$

where $j$ is the serial number of bending operation and $k$ is the last bending operation number before the inequality $\Delta \geq H$ holds true, when plastic deformation changes into elastic deformation over the entire cross section of the strip. Equation (7) was used to study the action of alternating elastoplastic bending on the formation of the mechanical properties of copper strips.

## EXPERIMENTAL

Commercial-purity copper strips of nominal sizes (thickness is $H_{\text{nom}} = 3.0$ mm, width is $B_{\text{nom}} = 20.0$ mm) were processed on a precision ARKU 25/21 (EcoMaster25) leveler with work rolls of diameter $D = 25$ mm located at a center distance $L = 28$ mm [4]. The gap range at the entrance is $G_1 = 2.25$–$2.75$ mm for a nominal strip thickness $H_{\text{nom}} = 3.0$ mm according to the setup nomogram of the EcoMaster25 machine. These limiting sizes of the gap $G_1$ were chosen to perform experiments. Using Eqs. (1)–(7), we calculated the relative strains and the true principal strain intensities for a nominal thickness of 3.0 mm at an entrance gap of 2.25 and 2.75 mm (Tables 1, 2). These tables are characterized by an increase in the radius of mean line curvature $R_{\text{cur}}$ of the strip and a decrease in the deformation and curvature $\gamma = R_{\text{cur}}^{-1}$ characteristics when the strip moves from the entrance in to the exit from the mangle. Simultaneously, elastically deformed layer thickness $\Delta$ increases; plastic deformation in cross section of the strip terminates at $\Delta \geq H$ (see Eq. (7)). For $G_1 = 2.25$ mm, the last bending operation is $k = 17$ before this condition is met; for $G_1 = 2.75$ mm, we have $k = 14$.

We performed four series of experiments. The main aim of the experiments in series 1 was to reveal the possibilities of changing the properties of copper strips in processing in the mangle at a gap $G_1 = 2.25$ mm at the entrance, when the maximum relative strain in outer rolls of the strip is 2.3% (see the first line in Table 1). The first strip was passed through the mangle 5 times, the second, 10 times, the third, 15, and the fourth, 20 times during deformation after softening heat treatment (HT: heating at 700°C for 10 min, water cooling). Standard plane specimens were cut from the strips and subjected to tension on an Instron 3382 tensile-testing machine according to the standard in [2]. It was found that yield strength $\sigma_{0.2}$ significantly increased in the strips and relative elongation $\delta$ noticeably decreased after five passes. A further increase in the number of passes weakly changed the mechanical properties [5].

Allowing for the experimental results obtained in series 1, other schemes of processing strips were used in series 2–4: the first strip was passed through the mangle one time; the second, two times; the third, three; the fourth, four; and the fifth strip, five times. These schemes differed only in the gap at the entrance: $G_1 = 2.25$ mm (minimum value for a strip thickness $H_{\text{nom}} = 3.0$ mm) for series 2 and 3 and $G_1 = 2.75$ mm (maximum value for a strip thickness $H_{\text{nom}} = 3.0$ mm) for series 4. The strips in the experiments of series 2 differed from those of series 3 and 4 in softening TO conditions: HT of the strips in series 2 is identical to

**Table 1.** Data for calculating the strains in alternating bending in EcoMaster25 leveler at $G_1 = 2.25$ mm and $G_{19} = 3.0$ mm (strip thickness is $H_{\text{nom}} = 3.0$ mm)

| $j$* | $G$, mm | $R_{\text{cur}}$, mm | $\gamma$, mm$^{-1}$ | $\varepsilon_{\text{out}}$, % | $e_{i_{\text{hard}}}$ | $e_{i_\Sigma}$ | $\Delta$, mm |
|---|---|---|---|---|---|---|---|
| 1 | 2.26 | 64.921 | 0.0154 | 2.311 | 0.0223 | 0.0112 | 0.250 |
| 2 | 2.29 | 68.716 | 0.0146 | 2.136 | 0.0211 | 0.0217 | 0.281 |
| 3 | 2.33 | 73.000 | 0.0137 | 2.055 | 0.0199 | 0.0317 | 0.292 |
| 4 | 2.38 | 79.625 | 0.0126 | 1.849 | 0.0183 | 0.0408 | 0.325 |
| 5 | 2.42 | 83.405 | 0.0120 | 1.767 | 0.0175 | 0.0500 | 0.340 |
| 6 | 2.46 | 89.808 | 0.0111 | 1.643 | 0.0163 | 0.0577 | 0.365 |
| 7 | 2.50 | 97.284 | 0.0103 | 1.518 | 0.0151 | 0.0653 | 0.395 |
| 8 | 2.54 | 106.118 | 0.0094 | 1.394 | 0.0138 | 0.0722 | 0.430 |
| 9 | 2.58 | 116.719 | 0.0086 | 1.269 | 0.0126 | 0.0785 | 0.473 |
| 10 | 2.63 | 129.675 | 0.0077 | 1.144 | 0.0114 | 0.0842 | 0.525 |
| 11 | 2.67 | 145.874 | 0.0069 | 1.018 | 0.0101 | 0.0892 | 0.589 |
| 12 | 2.71 | 166.702 | 0.0060 | 0.892 | 0.0089 | 0.0937 | 0.673 |
| 13 | 2.75 | 194.475 | 0.0051 | 0.765 | 0.0076 | 0.0975 | 0.784 |
| 14 | 2.79 | 233.360 | 0.0043 | 0.639 | 0.0064 | 0.1007 | 0.939 |
| 15 | 2.83 | 291.688 | 0.0034 | 0.512 | 0.0051 | 0.1032 | 1.173 |
| 16 | 2.88 | 388.903 | 0.0026 | 0.384 | 0.0038 | 0.1051 | 1.562 |
| 17 | 2.92 | 583.342 | 0.0017 | 0.256 | 0.0026 | 0.1064 | 2.339 |
| 18 | 2.96 | 1166.67 | 0.00086 | 0.128 | 0.0013 | 0.1071 | 4.673 |
| 19 | 3.00 | $\infty$ | 0 | 0 | 0 | — | — |

* Bending operation number.

that in series 1, and the strips of series 3 and 4 were held at 700°C for 30 min and then water cooled. The longitudinal strip speeds in the EcoMaster25 leveler was 3 m/min in the experiments of all these series.

## RESULTS AND DISCUSSION

The real copper strip thicknesses were found to differ from the nominal thickness, and the average thickness was $H = 2.87$ mm.

To estimate the relative strains ($\varepsilon_{\text{out}}$) and the true principal strain intensities ($e_i$), we performed calculations for the found average strip thickness at $G_1 = 2.25$ and 2.75 mm. The calculation results are given in Tables 3 and 4. It should be noted that the values presented in Tables 1 and 2 can be used to analyze the general problems of formation of the mechanical properties of copper strips after processing on a mangle. As follows from a comparison of the data in Tables 1–4, partial strain $\varepsilon_{\text{out}}$, the growth intensity of the elastically deformed layer $\Delta$, and the dynamics of changing the cumulative true principal strain intensity $e_{i_\Sigma}$ are radically different for different thicknesses in some cases.

This finding can be illustrated using the curves of changing the main indices that characterize the plastic deformation determining the change in the mechanical properties (cumulative true principal strain intensity $e_{i_\Sigma}$) and limit the propagation of plastic deformation over the cross section of the strip $\Delta$ when it moves from the entrance in the mangle to the exit from it (Figs. 2a, 2b). As follows from these curves, the geometric and deformation conditions of multiple elastoplastic bending with a decreasing radius of curvature substantially depend on the difference between strip thickness $H$ and roll gap $G_1$ at the entrance in the mangle.

All strips were subjected to tension [2]. The results of testing the mechanical properties before and after processing on the EcoMaster25 mangle are presented in Table 5. It is seen that all mechanical properties of the softened copper strips change radically after the first pass, the yield strength changes most strongly, and the character of changing the properties of the strips in the experiments of series 4 differs substantially from the changes in the properties of the strips of

**Table 2.** Data for calculating the strains in alternating bending in EcoMaster25 leveler at $G_1 = 2.75$ mm and $G_{19} = 3.0$ mm (strip thickness is $H_{\text{nom}} = 3.0$ mm)

| $j$ | $G$, mm | $R_{\text{cur}}$, mm | $\gamma$, mm$^{-1}$ | $\varepsilon_{\text{out}}$, % | $e_{i_{\text{hard}}}$ | $e_{i_\Sigma}$ | $\Delta$, mm |
|---|---|---|---|---|---|---|---|
| 1 | 2.750 | 194.48 | 0.0051 | 0.765 | 0.0076 | 0.0038 | 0.784 |
| 2 | 2.764 | 205.91 | 0.0049 | 0.723 | 0.0072 | 0.0074 | 0.830 |
| 3 | 2.778 | 218.78 | 0.0046 | 0.681 | 0.0068 | 0.0108 | 0.881 |
| 4 | 2.792 | 233.36 | 0.0043 | 0.639 | 0.0064 | 0.0140 | 0.939 |
| 5 | 2.806 | 250.02 | 0.0040 | 0.596 | 0.0059 | 0.0170 | 1.006 |
| 6 | 2.819 | 269.25 | 0.0037 | 0.554 | 0.0055 | 0.0197 | 1.083 |
| 7 | 2.833 | 291.69 | 0.0034 | 0.512 | 0.0051 | 0.0223 | 1.173 |
| 8 | 2.847 | 318.20 | 0.0031 | 0.469 | 0.0047 | 0.0246 | 1.279 |
| 9 | 2.861 | 350.02 | 0.0029 | 0.427 | 0.0043 | 0.0268 | 1.406 |
| 10 | 2.875 | 388.91 | 0.0026 | 0.384 | 0.0038 | 0.0287 | 1.562 |
| 11 | 2.889 | 437.51 | 0.0023 | 0.342 | 0.0034 | 0.0304 | 1.756 |
| 12 | 2.903 | 500.01 | 0.0020 | 0.299 | 0.0030 | 0.0319 | 2.006 |
| 13 | 2.917 | 583.35 | 0.0017 | 0.256 | 0.0026 | 0.0332 | 2.339 |
| 14 | 2.931 | 700.01 | 0.0014 | 0.214 | 0.0021 | 0.0342 | 2.806 |
| 15 | 2.944 | 875.01 | 0.0011 | 0.171 | 0.0017 | 0.0351 | 3.506 |
| 16 | 2.958 | 1166.7 | 0.0009 | 0.128 | 0.0013 | 0.0357 | 4.673 |
| 17 | 2.972 | 1750.0 | 0.0006 | 0.0856 | 0.0009 | 0.0362 | 7.010 |
| 18 | 2.986 | $\infty$ | 0 | 0 | 0 | — | — |

**Table 3.** Data for calculating the strains in alternating bending in EcoMaster25 leveler at $G_1 = 2.25$ mm and $G_{19} = 3.0$ mm (strip thickness is $H_{\text{nom}} = 2.87$ mm)

| $j$ | $G$, mm | $R_{\text{cur}}$, mm | $\gamma$, mm$^{-1}$ | $\varepsilon_{\text{out}}$, % | $e_{i_{\text{hard}}}$ | $e_{i_\Sigma}$ | $\Delta$, mm |
|---|---|---|---|---|---|---|---|
| 1 | 2.25 | 80.024 | 0.0125 | 1.762 | 0.0175 | 0.0088 | 0.326 |
| 2 | 2.29 | 83.844 | 0.0119 | 1.683 | 0.0167 | 0.0171 | 0.341 |
| 3 | 2.33 | 90.398 | 0.0111 | 1.563 | 0.0155 | 0.0249 | 0.367 |
| 4 | 2.38 | 100.06 | 0.0100 | 1.414 | 0.0140 | 0.0319 | 0.406 |
| 5 | 2.42 | 109.38 | 0.0091 | 1.295 | 0.0129 | 0.0388 | 0.443 |
| 6 | 2.46 | 120.69 | 0.0083 | 1.175 | 0.0117 | 0.0442 | 0.489 |
| 7 | 2.50 | 129.63 | 0.0077 | 1.095 | 0.0109 | 0.0496 | 0.524 |
| 8 | 2.54 | 145.83 | 0.0069 | 0.974 | 0.0097 | 0.0545 | 0.589 |
| 9 | 2.58 | 166.67 | 0.0060 | 0.854 | 0.0085 | 0.0586 | 0.672 |
| 10 | 2.63 | 205.88 | 0.0049 | 0.692 | 0.0069 | 0.0622 | 0.829 |
| 11 | 2.67 | 250.00 | 0.0040 | 0.571 | 0.0057 | 0.0650 | 1.005 |
| 12 | 2.71 | 291.67 | 0.0034 | 0.490 | 0.0049 | 0.0675 | 1.172 |
| 13 | 2.75 | 388.89 | 0.0026 | 0.368 | 0.0037 | 0.0693 | 1.561 |
| 14 | 2.79 | 583.33 | 0.0017 | 0.245 | 0.0025 | 0.0706 | 2.339 |
| 15 | 2.83 | 1166.67 | 0.0009 | 0.123 | 0.0010 | 0.0711 | 4.672 |
| 16 | 2.88 | $\infty$ | 0 | 0 | 0 | — | — |

**Table 4.** Data for calculating the strains in alternating bending in EcoMaster25 leveler at $G_1 = 2.75$ mm and $G_{19} = 3.0$ mm (strip thickness is $H_{\text{nom}} = 2.87$ mm)

| $j$ | $G$, mm | $R_{\text{cur}}$, mm | $\gamma$, mm$^{-1}$ | $\varepsilon_{\text{out}}$, % | $e_{i_{\text{hard}}}$ | $e_{i_\Sigma}$ | $\Delta$, mm |
|---|---|---|---|---|---|---|---|
| 1 | 2.750 | 397.74 | 0.0025 | 0.360 | 0.0036 | 0.0018 | 1.594 |
| 2 | 2.764 | 448.73 | 0.0022 | 0.319 | 0.0032 | 0.0034 | 1.800 |
| 3 | 2.778 | 500.01 | 0.0020 | 0.286 | 0.0029 | 0.0049 | 2.006 |
| 4 | 2.792 | 583.34 | 0.0017 | 0.245 | 0.0025 | 0.0061 | 2.339 |
| 5 | 2.806 | 700.01 | 0.0014 | 0.206 | 0.0020 | 0.0071 | 2.806 |
| 6 | 2.819 | 921.05 | 0.0011 | 0.156 | 0.0016 | 0.0079 | 3.690 |
| 7 | 2.833 | 1166.7 | 0.0009 | 0.123 | 0.0012 | 0.0085 | 4.673 |
| 8 | 2.847 | 1944.4 | 0.0005 | 0.074 | 0.0007 | 0.0089 | 7.783 |
| 9 | 2.861 | 3500.0 | 0.0003 | 0.041 | 0.0004 | 0.0091 | 14.006 |
| 10 | 2.875 | ∞ | 0 | 0 | 0 | — | — |

series 2 and 3. The last finding is explained by the fact that real strips differ from the strips of nominal sizes in thickness: as follows from Fig. 2, a thickness deviation of only 4.3% exerts the maximum effect at a large gap $G_1$ at the entrance. This finding is supported by Eq. (3), where the radius of curvature of the neutral section of a strip $R_{\text{cur}}$ is a function of the difference $H - G$ at a constant center distance $L$ of rolls.

Using the indicator diagrams obtained during the tensile tests of strips using the technique from [5], we determined equations to describe the flow curves of copper strips before and after processing on the EcoMaster25 leveler (Table 6). The flow curves equations adequately reflect the experimental data, which is indicated by coefficients of correlation $r$ determined in the $\ln(\sigma - \sigma_{0.2})$–$\ln e_i$ coordinates for a linearized flow curve. In the general form, the flow curves equations can be written as

$$\sigma = \sigma_{0.2} + Be_i^n. \tag{8}$$

Coefficients $B$ and $n$ in the right-hand side of Eq. (8) change substantially after the first pass and more weakly after the next passes. In the experiments of series 4, coefficients $B$ and $n$ remain almost unchanged after the first pass.

In the state after softening HT, the copper strips are hardened due to cold plastic deformation; as a result, their yield strength $\sigma_{0.2}$ and ultimate tensile strength $\sigma_u$ increase. We designate the yield strength after hardening as $\sigma_{0.2_{\text{hard}}}$, use Eq. (8), and determine true principal strain intensity $e_{i_{\text{hard}}}$ as the measure of plastic deformation that causes hardening,

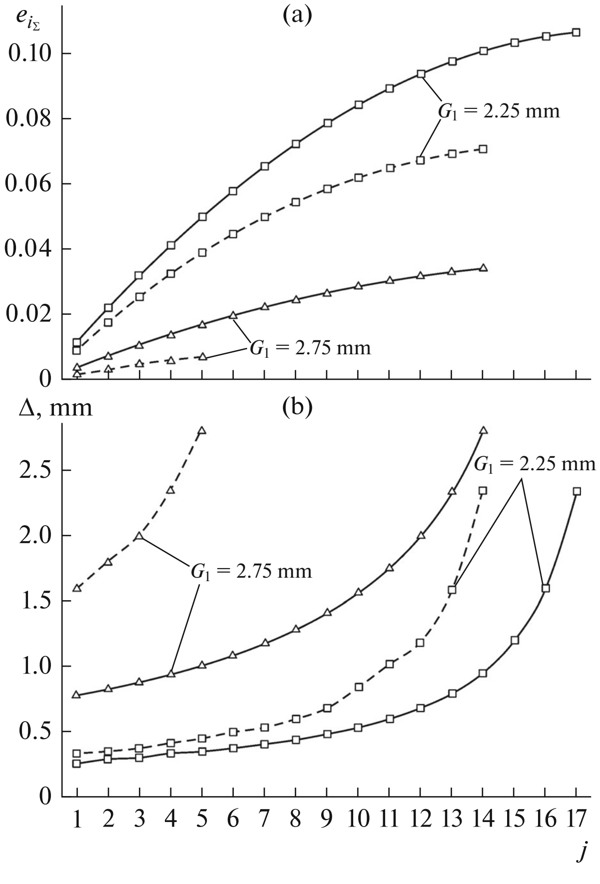

**Fig. 2.** Changes in (a) cumulative true principal strain intensity $e_{i_\Sigma}$ and (b) elastically deformed layer thickness Δ during the motion of a copper strip (—) 3.0 and (– – –) 2.87 mm thick in EcoMaster25 mangle ($j$ is bending operation number).

**Table 5.** Mechanical properties of copper strips before and after processing on a EcoMaster25 leveler

| Specimen | Number of passes | Gap |  | Tensile properties |  |  |  |
|---|---|---|---|---|---|---|---|
|  |  | at entrance | at exit | $\sigma_{0.2}$ | $\sigma_u$ | $\delta$ | $\delta_{un}$ |
|  |  |  |  | MPa |  | % |  |
| Experiments of series 1 |  |  |  |  |  |  |  |
| 1-0 | 0 | – | – | 39 | 206 | 57.29 | 47.22 |
| 1-1 | 5 | 2.25 | 3.0 | 179 | 224 | 38.37 | 27.25 |
| 1-2 | 10 | 2.25 | 3.0 | 188 | 224 | 39.24 | 28.34 |
| 1-3 | 15 | 2.25 | 3.0 | 179 | 224 | 36.18 | 23.26 |
| 1-4 | 20 | 2.25 | 3.0 | 185 | 226 | 37.78 | 20.25 |
| Experiments of series 2 |  |  |  |  |  |  |  |
| 2-0 | 0 | – | – | 31 | 206 | 52.72 | 46.81 |
| 2-1 | 1 | 2.25 | 3.0 | 150 | 218 | 44.58 | 28.68 |
| 2-2 | 2 | 2.25 | 3.0 | 158 | 221 | 43.19 | 26.76 |
| 2-3 | 3 | 2.25 | 3.0 | 171 | 223 | 40.92 | 24.88 |
| 2-4 | 4 | 2.25 | 3.0 | 179 | 224 | 40.01 | 23.89 |
| 2-5 | 5 | 2.25 | 3.0 | 175 | 223 | 40.19 | 24.79 |
| Experiments of series 3 |  |  |  |  |  |  |  |
| 3-0 | 0 | – | – | 31 | 210 | 53.77 | 39.53 |
| 3-1 | 1 | 2.25 | 3.0 | 133 | 218 | 42.56 | 30.18 |
| 3-2 | 2 | 2.25 | 3.0 | 154 | 220 | 43.95 | 25.57 |
| 3-3 | 3 | 2.25 | 3.0 | 164 | 221 | 42.38 | 26.26 |
| 3-4 | 4 | 2.25 | 3.0 | 175 | 223 | 40.71 | 23.90 |
| 3-5 | 5 | 2.25 | 3.0 | 176 | 223 | 37.24 | 23.92 |
| Experiments of series 4 |  |  |  |  |  |  |  |
| 4-0 | 0 | – | – | 35 | 210 | 56.25 | 43.75 |
| 4-1 | 1 | 2.75 | 3.0 | 43 | 212 | 55.36 | 43.17 |
| 4-2 | 2 | 2.75 | 3.0 | 49 | 211 | 59.62 | 40.71 |
| 4-3 | 3 | 2.75 | 3.0 | 52 | 212 | 57.69 | 41.11 |
| 4-4 | 4 | 2.75 | 3.0 | 48 | 211 | 58.09 | 40.93 |
| 4-5 | 5 | 2.75 | 3.0 | 45 | 211 | 55.98 | 42.71 |

$$e_{i_{\text{hard}}} = \exp\left(\frac{1}{n}\ln\frac{\sigma_{0.2_{\text{hard}}} - \sigma_{0.2}}{B}\right). \quad (9)$$

For comparison, we give the values of $e_{i_\Sigma}$ from Tables 3 and 4 and the values of $e_{i_{\text{hard}}}$ calculated by Eq. (9) for the experiments of series 2–4,

| Series | 2 | 3 | 4 |
|---|---|---|---|
| $e_{i_\Sigma}$ | 0.0706 | 0.0706 | 0.0071 |
| $e_{i_{\text{hard}}}$ | 0.1268 | 0.0962 | 0.0049 |

The discrepancy between $e_{i_\Sigma}$ and $e_{i_{\text{hard}}}$ can be explained by the average copper strip thickness ($H$ = 2.87 mm) used in the calculations, while the real strip thickness oscillated in the range 2.81–2.95 mm because of the fact that the strips were cut off from a hot-rolled sheet. Nevertheless, the data obtained in each series of experiments have the same order of magnitude, which can serve as the basis for a positive conclusion regarding the adequacy of the proposed model for determining the sizes and the interaction of the plastic and elastic parts of strips during their mul-

**Table 6.** Flow curve equations of copper strips before and after processing on an EcoMaster25 leveler

| State of strip | Flow curve equation | $r$* |
|---|---|---|
| Experiments of series 1 | | |
| After HT | $\sigma = 39 + 704e_i^{0.8397}$ | 0.9994 |
| After 5 passes | $\sigma = 179 + 380e_i^{0.8661}$ | 0.9954 |
| After 10 passes | $\sigma = 180 + 249e_i^{0.6561}$ | 0.9956 |
| After 15 passes | $\sigma = 179 + 203e_i^{0.5801}$ | 0.9923 |
| After 20 passes | $\sigma = 185 + 206e_i^{0.5771}$ | 0.9956 |
| Experiments of series 2 | | |
| After HT | $\sigma = 31 + 672e_i^{0.8382}$ | 0.9986 |
| After 1 pass | $\sigma = 150 + 307e_i^{0.7137}$ | 0.9967 |
| After 2 passes | $\sigma = 158 + 292e_i^{0.6995}$ | 0.9962 |
| After 3 passes | $\sigma = 171 + 202e_i^{0.551}$ | 0.9851 |
| After 4 passes | $\sigma = 179 + 228e_i^{0.6435}$ | 0.9942 |
| After 5 passes | $\sigma = 175 + 242e_i^{0.6609}$ | 0.9944 |
| Experiments of series 3 | | |
| After HT | $\sigma = 31 + 719e_i^{0.8341}$ | 0.9993 |
| After 1 pass | $\sigma = 133 + 465e_i^{0.8388}$ | 0.9998 |
| After 2 passes | $\sigma = 154 + 328e_i^{0.7507}$ | 0.9973 |
| After 3 passes | $\sigma = 164 + 292e_i^{0.7277}$ | 0.9964 |
| After 4 passes | $\sigma = 175 + 301e_i^{0.7779}$ | 0.9984 |
| After 5 passes | $\sigma = 176 + 270e_i^{0.7129}$ | 0.9971 |
| Experiments of series 4 | | |
| After HT | $\sigma = 35 + 717e_i^{0.8447}$ | 0.9988 |
| After 1 pass | $\sigma = 43 + 666e_i^{0.8116}$ | 0.9994 |
| After 2 passes | $\sigma = 49 + 666e_i^{0.827}$ | 0.9992 |
| After 3 passes | $\sigma = 52 + 655e_i^{0.8205}$ | 0.9994 |
| After 4 passes | $\sigma = 48 + 655e_i^{0.8139}$ | 0.9994 |
| After 5 passes | $\sigma = 45 + 658e_i^{0.8116}$ | 0.9994 |

* $r$ is the coefficient of correlation.

tiple elastoplastic bending on the EcoMaster25 mangle with a decreasing radius of curvature and for estimating the related hardening. This is true of commercial-purity copper strips subjected to preliminary softening HT, after which the metal has a low yield strength and a high deformability potential.

## CONCLUSIONS

(1) A model was developed to determine the geometric and deformation characteristics of metallic strips in processing on a leveler during alternating elastoplastic bending with a decreasing radius of curvature.

(2) The results of experiments on processing of commercial-purity copper strips, which were subjected to preliminarily softening HT, on an EcoMaster25 leveler showed that the developed model satisfactorily described the real deformation conditions in the mangle.

(3) The maximum effect of alternating elastoplastic bending of commercial-purity copper was found to consist in a significant (by three–five times) increase in yield strength $\sigma_{0.2}$ in one pass at the minimum gap from the gap range given by a nomogram (2.25 mm) at the entrance into the EcoMaster25 mangle. When the gap was increased to the recommended maximum value (2.75 mm), this effect became much weaker: $\sigma_{0.2}$ increased by 23–49%.

(4) Upon elastoplastic bending with a decreasing radius of curvature, the thickness of the central (elastically deformed) zone of the strip increases when a strip moves from the entrance into to the exit from the EcoMaster25 mangle. Using the developed model, we were able to find the boundary of alternating deformation at which the entire cross section of the strip passes to the elastic deformation zone.

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