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ANALYSIS AND CALCULATION OF SPREAD AND LEAD OF ALUMINUM ALLOYS FLOW DURING HOT DEFORMATION

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This paper presents an in-depth analysis of the relationship between kinematic rolling parameters and the physical and mechanical properties of aluminum alloys. For the first time, a refined method for calculating spread and lead is proposed, which, unlike existing techniques, accounts for the dynamic changes in deformation resistance throughout the entire deformation zone. This allowed for the establishment of more accurate functional dependencies between the reduction degree, rolling speed, and the direction of metal flow in both longitudinal and transverse directions. Special attention is paid to the influence of the material's rheological properties on the non-uniformity of velocity distribution in the contact and internal layers of the workpiece.

A comprehensive approach was applied in this study, combining theoretical analysis of the deformation zone kinematics and mathematical modeling of plastic flow processes. The computational part is based on the principles of continuum mechanics, considering the temperature-velocity factor and contact friction conditions typical for the hot deformation of aluminum alloys. To verify the obtained data, a comparative analysis with experimental research results was conducted.

It is proved that traditional calculation models exhibit significant errors when working with high-plasticity aluminum alloys under high-temperature conditions. The refined calculation algorithm ensures high convergence with experimental data (error minimized to 5%). It was established that precise regulation of lead parameters at a heating temperature of both the workpiece and the tool within 250–350°C prevents surface defects such as laps and edge non-uniformity, which is critically important for rolling parts with complex cross-sections.

The implementation of the developed method into the production process significantly improves the geometric precision of the finished rolled products and stabilizes the mill setup process. This minimizes the volume of technological scrap and ensures the rational use of expensive raw materials. The economic effect is achieved by reducing energy consumption for scrap reprocessing and substantially increasing the yield of usable products. The research results can be recommended for use by design bureaus for roll pass design and the development of automated control systems for rolling processes.

Keywords: *aluminum alloys, workpieces, plastic deformation, hot rolling, spread, lead, technological process.*

Eq. 36. Fig. 4. Ref. 7.

1. Problem formulation

There is an insufficient amount of existing scientific materials for studying the relationship between the kinematic parameters of the deformation zone and the non-uniformity of velocity distribution in the internal layers of aluminum alloy workpieces during hot rolling. The absence of refined mathematical models that integrate temperature-velocity factors and contact friction conditions limits the possibilities for effective roll pass design to obtain parts with complex cross-sections without defects.

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2. The purpose of the work

The study is aimed at improving the prediction accuracy of form change parameters of aluminum alloys during hot rolling. The primary task is to develop and substantiate a refined method for calculating the spread and lead of metal flow, which allows for the optimization of consumption coefficients in the manufacturing of forgings and parts with complex cross-sections.

3. Presentation of the main material

Previous experimental studies on determining spread during hot deformation [1-3] have shown that regarding the nature of change in these parameters—depending on the heating temperatures of the rolls and workpieces, as well as the degree of deformation during rolling—only their quantitative values change. These values depend on the degree of deformation and the geometric ratios of the roll pass and the workpiece.

Analysis of the experimental data presented in Fig. 1 showed that the difference in spread values obtained during the rolling of workpieces in rolls at a temperature of 20°C compared to those heated to temperatures of 250–350°C (an interval characterized by the constancy of spread values) constitutes, for any degree of workpiece deformation in the studied range (30–50%), a value determined by the formula:

$$\frac{\Delta b_{20}}{b_0} - \frac{\Delta b_{350}}{b_0} = \frac{\Delta h}{h_0}(tg\alpha - tg\alpha_1) \qquad (1)$$

where: Δh – absolute deformation (reduction), mm; h_0 , b_0 – height and width of the initial workpiece, mm; Δb_{20}, Δb_{350}– spread obtained during rolling of workpieces in rolls with temperatures of 20°C and 250–350°C, respectively; $tg\alpha$, $tg\alpha_1$ – slope angles that determine the dependence of spread on the degree of deformation during rolling at temperatures of 20°C and 250–350°C, respectively.

For a round workpiece b_0 = h_0, therefore:

$$\Delta b20\ -\ \Delta b350\ =\ \Delta h\,(tg\alpha\ -\ tg\alpha 1)\ =\ \Delta h\cdot K_{\text{уш}}^{\text{и}}, \qquad (2)$$

where: $K_{\text{уш}}^{\text{и}}$- temperature coefficient of spread, which depends on the heating temperature of the rolls/dies; $\Delta h \cdot K_{\text{уш}}^{\text{и}}$- the value that determines the difference between the spread obtained during hot rolling and traditional rolling.

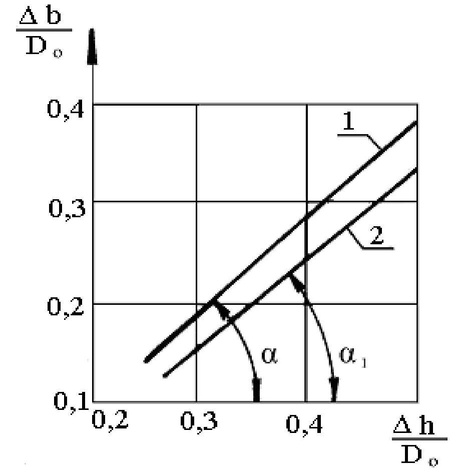

Fig. 1. Dependence of spread on the degree of deformation during rolling of round cross-section workpieces in plain rolls at temperatures of: 1 – 20 °C; 2 – 250 – 350 °C.

During the rolling of workpieces in pass sequences such as oval–rhombus, oval–square, oval–rhombus–round, etc., the absolute reduction Δh is expressed as the difference between the workpiece width bз, obtained after rolling in the previous pass and the height of the subsequent pass| hк|. Therefore, the spread values during rolling in dies heated to 250–350°C will be determined similarly, but taking into account the geometric shape ratios of the pass and the workpiece.

$$\Delta b_{20} - \Delta b_{350} = (b_{\text{з}} - h_{\text{к}})K_{\text{уш}}^{\text{и}} = \Delta h \cdot K_{\text{уш}}^{\text{и}}. \qquad (3)$$

During hot rolling, the spread values determined by formulas for traditional rolling must be adjusted taking into account the values obtained from the calculations using the methodology described above. This implies that when rolling workpieces in plain rolls and passes, their width should be reduced accordingly by the values provided in formulas (1) - (3).

Fig. 2 presents the dependencies of spread on the degree of deformation during the rolling of workpieces at temperatures of 20°C and 250–350°C. The values of tgα, tgα1 ||, can be easily determined from this graph.

In the monograph by Dr. S.O. Skriabin [4], formulas are provided for determining the spread during traditional rolling of aluminum workpieces, which are an integral part of the mathematical model for calculating the spread during workpiece rolling.

According to formula (3), the spread during hot rolling of aluminum alloy workpieces in passes of various systems will be determined by the following formulas:

- for round cross-section workpieces in oval passes:

$$\Delta \mathrm{b} = \text{К}_{\text{уш}}^{\text{ов}}\sqrt{(d-h_{\text{ов}})0{,}5D_{\text{к}}^{\text{ов}}\frac{d-h_{\text{ов}}}{d}} - (d-h_{\text{ов}})K_{\text{уш}}^{\text{и}} \tag{4}$$

where: the expression $(d-h_{\text{ов}})K_{\text{уш}}^{\text{и}}$ - is the value that determines the difference between the spread obtained during hot rolling and traditional rolling; $K_{\text{уш}}^{\text{и}}$ - is the temperature coefficient of spread, which depends on the heating temperature of the rolls; $\text{К}_{\text{уш}}^{\text{ов}}$- is the coefficient that accounts for the influence of non-uniform deformation across the width and height of the workpiece on spread, depending on the curvature of the oval pass [4].

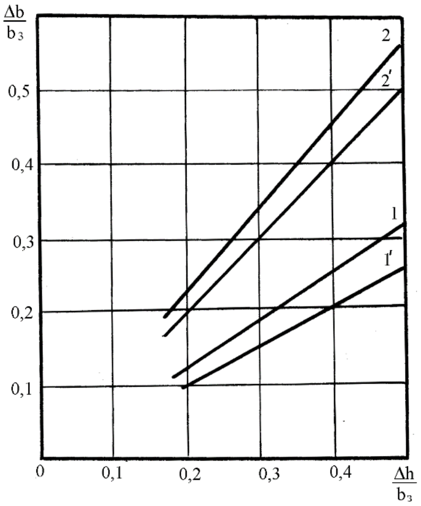

Fig. 2. Dependence of spread on the degree of deformation during the rolling of workpieces in rolls at temperatures of: 1, 1´ – 20 °C (rolling of a round workpiece in an oval pass); 2, 2´ – 250 – 350 °C (rolling of an oval workpiece in a rhombus pass).

As a result of the experimental and calculated data, the following formula for determining the lead was obtained $\text{К}_{\text{уш}}^{\text{ов}}$

$$\text{К}_{\text{уш}}^{\text{ов}} = -\sqrt{0{,}0582\iota^2 - 0{,}02123\iota + 0{,}2015} + 0{,}2265\iota - 0{,}049 \tag{5}$$

where $h_{\text{ов}}$ - height of the oval pass, mm; d - diameter of the deformable workpiece, mm; $D_{\text{к}}^{\text{ов}}$- diameter of the oval pass, mm.

$$D_{\text{к}}^{\text{ов}} = A - \left(\frac{2}{3}\right)h_{\text{ов}}. \tag{6}$$

- A - center-to-center distance of the rolls (center distance), mm.
- oval workpieces in rhombus passes:

$$\Delta b = \text{К}_{\text{уш р}}^{\text{ов}}\sqrt{\left(b_{\text{ов з}} - h_{\text{р}}\right)\frac{D_{\text{к}}^{\text{р}}}{2}\frac{b_{\text{ов з}} - h_{\text{р}}}{b_{\text{ов з}}}} - \left(b_{\text{ов.з}} - h_p\right)K_{\text{уш}}^{\text{и}} \tag{7}$$

where: $\text{К}_{\text{уш р}}^{\text{ов}}$ - coefficient accounting for the influence of non-uniform deformation across the pass width on spread during the rolling of an oval workpiece in a rhombus pass [4]; $b_{\text{ов з}}$ - width of the oval workpiece, mm; hp - height of the rhombus pass, mm; $D_{\text{к}}^{\text{р}}$ - diameter of the rhombus pass, mm:

$$D_{\text{к}}^{\text{р}} = \text{А} - 0{,}5h_p. \tag{8}$$

As a result of processing the experimental and calculated data, the formula for determining $\text{К}_{\text{уш р}}^{\text{ов}}$ was obtained:

$$K_{\text{уш р}}^{\text{ов}} = \sqrt{2 - 0.000633\,\psi^2 + 0.00626\,\psi - 0.00336 + 0.00553\,\psi + 0.0437}. \tag{9}$$

where: ψ $= a_{\text{ов}} \times a_{\text{рз}}$, - axis ratios of the oval and rhombus workpieces, respectively.

- oval workpieces in square passes:

$$\Delta b = \text{К}_{\text{уш кв}}^{\text{ов}} \sqrt{(b_{\text{ов з}} - h_{\text{кв}}) \frac{D_{\text{к}}^{\text{кв}}}{2} \frac{b_{\text{ов з}} - h_{\text{кв}}}{b_{\text{ов з}}}} - (b_{\text{ов.з}} - h_{\text{кв}}) K_{\text{уш}}^{\text{и}} \tag{10}$$

where: $\text{К}_{\text{уш кв}}^{\text{ов}}$- coefficient accounting for the influence of non-uniform deformation across the pass width on spread during the rolling of an oval workpiece in a square pass, determined by formula (11) or according to [2]; hкв- height of the square pass, mm; $D_{\text{к}}^{\text{кв}}$- rolling diameter of the square pass, mm;

$$[K_{\text{уш ке}}^{\text{ов}} = \sqrt{0.751 a_{\text{ое}}^2 - 2.627 a_{\text{ое}} + 2.327} + 0.945 a_{\text{ое}} - 1.187;] \tag{11}$$

$$D_{\text{к}}^{\text{кв}} = A - (c^2 - 0{,}86\, r)(1{,}41\, c - 0{,}83\, r) \tag{12}$$

where: r - corner rounding radius at the apex, mm.

- rhombus workpieces in square passes, mm:

$$\Delta b = \text{К}_{\text{уш кв}}^{\text{ов}} \sqrt{(b_{\text{ов з}} - h_{\text{кв}}) \frac{D_{\text{к}}^{\text{кв}}}{2} \frac{b_{\text{ов з}} - h_{\text{кв}}}{b_{\text{ов з}}}} - (b_{\text{ов.з}} - h_{\text{кв}}) K_{\text{уш}}^{\text{и}} \tag{13}$$

where: $\text{К}_{\text{уш кв}}^{p}$- coefficient accounting for the influence of non-uniform deformation across the pass width on spread during the rolling of a rhombus workpiece in a square pass, determined by formula (14) or according to [2]; $b_{p\ \text{з}}$ - width of the rhombus workpiece, mm;

$$\text{К}_{\text{уш кв}}^{p} = \sqrt{0{,}0000551\text{a}_p{}^2 - 0{,}000136\text{a}_p + 0{,}000119} + 0{,}207\text{a}_p - 0{,}177 \tag{14}$$

- oval workpieces in round passes, mm:

$$\Delta b_{\text{кр}}^{\text{ов}} = \text{К}_{\text{кр}}^{\text{ов}} \sqrt{\left(b_{\text{ов з}} - d_{\text{кр}}\right) \frac{D_{\text{к}}^{\text{кр}}}{2} \frac{b_{\text{ов з}} - d_{\text{кр}}}{b_{\text{ов з}}}} - \left(b_{\text{ов.з}} - d_{\text{кр}}\right) K_{\text{уш}}^{\text{и}} \tag{15}$$

where: $\text{К}_{\text{кр}}^{\text{ов}}$ - coefficient accounting for the influence of non-uniform deformation across the pass width on spread during the rolling of an oval workpiece in a round pass [4]; d_0- size of the pass, mm; $D_{\text{к}}^{\text{кр}}$- diameter of the round pass, mm:

$$D_{\text{к}}^{\text{кр}} = A - 0{,}785\, d_o \tag{16}$$

- rhombus workpieces in round passes, mm:

$$\Delta b_{\text{кр}}^{\text{р}} = \text{К}_{\text{кр}}^{\text{р}} \sqrt{\left(b_{\text{р з}} - d_{\text{кр}}\right) \frac{D_{\text{к}}^{\text{кр}}}{2} \frac{b_{\text{р з}} - d_{\text{кр}}}{b_{\text{р з}}}} - \left(b_{\text{р.з}} - d_{\text{кр}}\right) K_{\text{уш}}^{\text{и}} \tag{17}$$

where: $\text{К}_{\text{кр}}^{\text{р}}$- coefficient accounting for the influence of non-uniform deformation across the pass width on spread during the rolling of a rhombus workpiece in a round pass [4].

The formulas for determining the spread belong to the second stage in the development of the spread theory according to A.I. Tselikov's gradation, meaning that the spread is proportional not only to the deformation but also to the length of the contact arc. Furthermore, the obtained formulas take into account the geometric shape ratios of the pass and the workpiece, as well as the non-uniformity of deformation across the pass width.

Formulas for determining the flow lead of aluminum alloys during hot deformation

Formulas known in the literature for determining lead can be conventionally divided into two groups:

- formulas related to determining the position of the critical angle on the contact surface (assuming the validity of the plane sections hypothesis);
- formulas that account for spread.

According to the plane sections hypothesis, it is assumed that the horizontal components of the velocity vector are uniformly distributed across the strip height and that no sticking zone exists. The neutral section of the strip is taken as the section passing through the neutral point on the contact surface where the shear stress is zero. Under these assumptions, calculations are considered satisfactory for so-called "low" deformation zones, where the ratio lд/hср > (rolling of thin strips), and the non-uniform distribution of deformations, stresses, and velocities across the strip height is negligible.

In the process of rolling workpieces on forging rolls, this ratio is significantly lower. Calculating the lead based on the neutral angle γ (τS = 0) under conditions of non-uniform velocity distribution of metal particles in the deformation zone leads to significant errors. This explains the discrepancy between calculated lead data and experimental results.

Calculations using lead formulas that account for spread also show major discrepancies. Currently, lead in rolling with spread has not been fully investigated. The main difficulty lies in the fact that the law governing the change in strip width along the rolls is unknown. Existing lead formulas that include spread are based on various, more or less substantiated assumptions regarding this law. Furthermore, the formulas provided in the literature do not account for the non-uniformity of deformation across the workpiece width, nor the geometric shape ratios of the pass and the workpiece.

Oval stretching passes are most commonly used. To determine the most applicable formula from those available in the literature for finding lead values during the rolling of aluminum alloy workpieces in oval passes, an investigation of lead was conducted alongside the study of spread. The obtained experimental data were compared with results calculated using formulas previously derived under the assumption of the plane sections hypothesis:

S. Fink's formula (discrepancy with experimental values of 20–30%);

$$S = \frac{[h_1 + D(1 - cos\gamma)]\, cos\,\gamma}{h_1} - 1;$$

Ekelund's formula (discrepancy of 30–35%);

$$S = 0{,}5\gamma^2\left[\left(\frac{D}{h_1}\right) - 1\right];$$

Dresden–Golovin's formula (discrepancy of 30–35%);

$$S = \frac{D}{(2h_1)\gamma^2};$$

G.S. Lavrukhin's formula (characterizes lead during flattening in passes; discrepancy of 20–25%);

$$S = \left(\frac{\upsilon + 1}{3\upsilon + 1}\right)^2\left(\frac{D}{h_1} - 1\right)\left(V\frac{\Delta h}{D} - \frac{1}{\mu\sqrt{2}}\frac{\Delta h}{D}\right)^2;$$

V.K. Smirnov's formula (for determining lead in passes; discrepancy of 15–25%);

$$S = \left(\frac{\gamma^2 R_p}{h_1}\right)100\%;$$

V.M. Martynov's formula (for rhombus passes; discrepancy of 30–40%);

$$S = 24\left(\frac{h_{oc} - \frac{hk}{2}}{h_{oc}}\right)^3 c$$

I.M. Pavlov's formula (discrepancy of 20–25%);

$$S_h = \left(\frac{B_\gamma}{B_2}\right)\left\{\frac{[D(1 - cos\,\gamma) + h]\, cos\,\gamma}{h}\right\} - 1;$$

B.P. Bakhtinov's formula (discrepancy of 25–30%);

$$S_h = c\left(\frac{b_к}{1{,}15\sqrt{R\Delta h}} - c\right)\frac{\Delta b_к}{b_к}.$$

Experimental studies on determining the lead during hot rolling have shown that the nature of change in this parameter—depending on the heating temperatures of the rolls and workpieces, as well as the degree of deformation during rolling in plain rolls and passes of various systems—is similar. Only their quantitative values change, depending on the degree of deformation and the geometric ratios of the pass and the workpiece.

Analysis of the experimental data presented in Fig. 3 showed that the difference in lead values obtained during the rolling of workpieces in rolls at a temperature of 20°C compared to those heated to 250–350°C (an interval characterized by the constancy of lead values) [5-7] constitutes, for any degree of workpiece deformation in the studied range (30–50%), a value determined as follows:

$$S_{350} - S_{20} = \frac{\Delta h}{h_o}(\backslash tg\alpha - \backslash tg\alpha_1) \tag{18}$$

$$S_{350} - S_{20} = \frac{\Delta h}{h_o}K_s^и \tag{19}$$

where: S_{350}, S_{20} - lead values obtained during the rolling of workpieces in rolls with heating temperatures of 250–350°C and 20°C, respectively; $K_s^и$ - temperature coefficient of lead, which depends on the roll heating temperature.

When rolling workpieces in pass systems such as oval–rhombus, oval–square, and oval–rhombus–round, the degree of deformation is expressed as the difference between the workpiece width b_3, obtained after rolling in the previous pass and the height of the subsequent pass |наступного $h_к$

Therefore, the lead values during rolling in rolls heated to 250–350°C will be determined similarly, but taking into account the geometric shape ratios of the pass and the workpiece.

$$S_{350} - S_{20} = \frac{b_з - h_к}{b_з} \cdot K_s^и \tag{20}$$

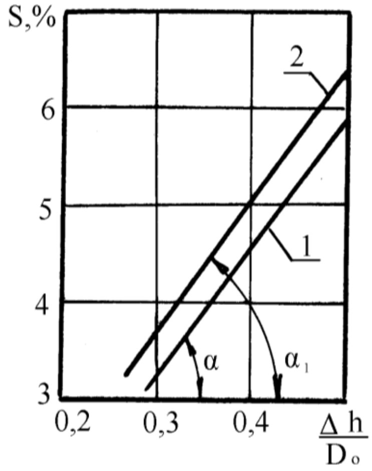

Fig. 3. Dependence of lead on the degree of deformation during the rolling of round cross-section workpieces in plain rolls at temperatures of: 1 – 20 °C; 2 – 250 – 350 °C.

During hot rolling, the lead values determined by formulas for traditional rolling must be adjusted taking into account the values obtained from calculations using the methodology described above. This implies that when rolling workpieces in plain rolls and passes, the required working rolling length will be determined by the following formulas:

- for rolling round cross-section workpieces in plain rolls:

$$l_p = \frac{l}{1 + \left(S_{20} + \frac{\Delta h}{h_0} \cdot K_s^и\right)} \tag{21}$$

- for rolling workpieces in passes:

$$l_p = \frac{l}{1 + \left(S_{20} + \frac{b_з - h_к}{b_з} K_s^и\right)} \tag{22}$$

where: l - required profile length, mm; l_p - working length of the roll, mm; S_{20} - lead (forward slip) in traditional technology.

Fig. 4 presents the dependencies of lead on the degree of deformation during the rolling of workpieces at temperatures of 20°C and 250–350°C. The values of tgα, tgα1, can be easily determined from this graph.

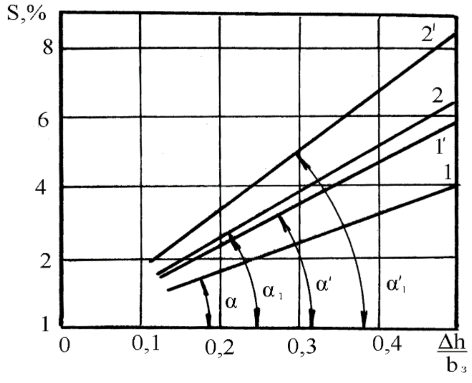

Fig. 4. Dependence of lead on the degree of deformation during rolling in forging dies at temperatures of: 1, 1' – 20 °C (rolling of a round workpiece in an oval pass); 2, 2' – 250 – 350 °C (rolling of an oval workpiece in a rhombus pass).

In study [4], formulas are provided for determining the lead during traditional rolling of aluminum alloy workpieces in various pass systems, which are an integral part of the mathematical model for calculating the lead during hot rolling.

Thus, during rolling:

- for round workpieces in oval passes, the lead is determined by the formula:

$$S_{\text{ов}} = \mathrm{i}\frac{d-h_{\text{ов}}}{d}\mathrm{К}_{s\ \text{ов}} + 0{,}5\left(1-\frac{1}{2\mu}\sqrt{\frac{\Delta h}{R_{\text{р}}^{\text{ов}}}}\right)\frac{\Delta h}{D_{\text{р}}^{\text{ов}}} + \frac{d-h_{\text{ов}}}{d}\cdot K_s^{\text{и}} \tag{23}$$

where: the expression $\frac{d-h_{\text{ов}}}{d}\cdot K_s^{\text{и}}$ - the value that determines the difference between the lead obtained during hot rolling and traditional rolling; i -Rк / R з - coefficient accounting for the influence of the oval pass curvature on deformation non-uniformity; Rк - radius of the oval pass, mm; Rз, d - radius and diameter of the workpiece, respectively; $h_{\text{ов}}$ - height of the oval pass, mm; μ – friction coefficient; Δh ов - absolute degree of deformation (reduction); Ks.ов - coefficient accounting for the influence of non-uniform deformation across the workpiece width on the lead, depending on the curvature of the oval pass [4]; $R_{\text{р}}^{\text{ов}}$i $D_{\text{р}}^{\text{ов}}$ - working radius and diameter of the oval pass, mm:

$$R_{\text{р}}^{\text{ов}} = 0{,}5(A-h_{\text{ов}}). \tag{24}$$

The processing of experimental and calculated data allowed for the representation of the dependence of the Ks ов coefficient on i = Rк/ Rз by the following formula:

$$\mathrm{К}_s = \sqrt{270{,}569i^2-516{,}265i+248{,}728}-16{,}455i+15{,}714. \tag{25}$$

- oval workpiece in a square pass:

$$S_{\text{кв}}^{\text{ов}} = a_{\text{ов}}\frac{b_{\text{ов з}}-h_{\text{кв}}}{b_{\text{ов з}}}\mathrm{К}_{s\ \text{кв}}^{\text{ов}} + 0{,}5\left(1-\frac{1}{2\mu}\sqrt{\frac{\Delta h}{R_{\text{р}}^{\text{кв}}}}\right)\frac{\Delta h}{D_{\text{р}}^{\text{кв}}} + \frac{b_{\text{ов.з}}-h_{\text{кв}}}{b_{\text{ов.з}}}K_s^{\text{и}} \tag{26}$$

where: $a_{\text{ов}}$ - axis ratio of the oval workpiece; $b_{\text{ов}}$ - width of the oval workpiece, mm; $\mathrm{К}_{s\ \text{кв}}^{\text{ов}}$- coefficient accounting for the non-uniformity of deformation across the width of the square pass during the rolling of an oval workpiece [4]; $h_{\text{кв}}$, $R_{\text{р}}^{\text{кв}}$, $D_{\text{р}}^{\text{кв}}$ - height, working radius, and diameter of the square pass, respectively, mm:

$$R_{\text{р}}^{\text{кв}} = 0{,}5(A-h_{\text{кв}}); \tag{27}$$

- rhombus workpiece in a square pass:

$$S_{\text{кв}}^{\text{р}} = a_{\text{р}_\text{з}}\frac{b_{\text{р з}}-h_{\text{кв}}}{b_{\text{р з}}}\mathrm{К}_{s\ \text{кв}}^{\text{ов}} + 0{,}5\left(1-\frac{1}{2\mu}\sqrt{\frac{\Delta h}{R_{\text{р}}^{\text{кв}}}}\right)\frac{\Delta h}{D_{\text{р}}^{\text{кв}}} + \frac{b_{\text{р.з}}-h_{\text{р}}}{b_{\text{р.з}}}K_s^{\text{и}} \tag{28}$$

where: $a_{\text{р}_\text{з}}$ - axis ratio of the rhombus workpiece; $h_{\text{кв}}$ - height of the square pass, mm; $b_{\text{р з}}$ - width (dimension) of the rhombus workpiece, mm;

$\mathrm{К}_{s\ \text{кв}}^{\text{ов}}$ - coefficient accounting for the non-uniformity of deformation across the width of the square pass during the rolling of a rhombus workpiece [4].

As a result of data processing, the following formulas were derived for calculating $\mathrm{К}_{s\ \text{кв}}^{\text{ов}}$ i $\mathrm{К}_{s\ \text{кв}}^{\text{р}}$:

$$\mathrm{К}_{s\ \text{кв}}^{\text{ов}} = \sqrt{59{,}407\mathrm{a}^2 - 117{,}505\mathrm{a} + 59{,}184} - 7{,}732\mathrm{a} + 7{,}688; \tag{29}$$

$$\mathrm{К}_{s\ \text{кв}}^{\text{р}} = \sqrt{5{,}552\mathrm{a}^2 - 4{,}814\mathrm{a} - 0{,}716} + 2{,}390\mathrm{a} - 1{,}242. \tag{30}$$

- oval workpiece in a rhombus pass:

$$S_{350}^{\text{р}} = a_{\text{ов.з}}\frac{b_{\text{ов з}}-h_{\text{р}}}{b_{\text{ов з}}}\mathrm{К}_{s\ \text{р}}^{\text{ов}} + 0{,}5\left(1-\frac{1}{2\mu}\sqrt{\frac{\Delta h}{R_{\text{р}}^{\text{р}}}}\right)\frac{\Delta h}{D_{\text{р}}^{\text{р}}} + \frac{b_{\text{ов.з}}-h_{\text{р}}}{b_{\text{ов.з}}}\cdot K_s^{\text{и}} \tag{31}$$

where: $\mathrm{К}_{s\ \text{р}}^{\text{ов}}$- coefficient accounting for the non-uniformity of deformation across the width of the rhombus pass during the rolling of an oval workpiece [4].

$h_{\text{р}}$,$R_{\text{р}}^{\text{р}}$ и $D_{\text{р}}^{\text{р}}$- height, working radius, and diameter of the rhombus pass, respectively, mm;

$$R_{\text{р}}^{\text{р}} = 0{,}5(\mathrm{A}-h_{\text{р}}). \tag{32}$$

As a result of data processing, the formula for calculating $\mathrm{К}_{s\ \text{р}}^{\text{ов}}$ was obtained:

$$\mathrm{К}_{s\ \text{р}}^{\text{ов}} = \sqrt{0{,}057\psi^2 - 0{,}329\psi} + 0{,}489 - 0{,}246\psi + 0{,}780. \tag{33}$$

- oval workpiece in a round pass:

$$S_{кр}^{ов} = a_{ов_з}\frac{b_{ов\ з} - d_{кр}}{b_{ов\ з}}К_{s\ кр}^{ов} + 0{,}5\left(1 - \frac{1}{2\mu}\sqrt{\frac{\Delta h}{R_{р}^{кр}}}\right)\frac{\Delta h}{D_{р}^{кр}} + \frac{b_{ов.з} - d_{кр}}{b_{ов.з}}K_s^{и} \tag{34}$$

where: $К_{s\ кр}^{ов}$ - coefficient accounting for the non-uniformity of deformation across the width of the round pass during the rolling of an oval workpiece [4]; $b_{ов\ з}$ - workpiece diameter; $R_{р}^{кр}$ і $D_{р}^{кр}$- working radius and diameter of the round pass, respectively, mm:

$$R_{кр} = 0{,}5(А - h_{р}); \tag{35}$$

- rhombus workpiece in a round pass:

$$S_{кр}^{р} = a_{р_з}\frac{b_{p\ з} - d_{кр}}{b_{p.\ з}}К_{s\ кр}^{p} + 0{,}5\left(1 - \frac{1}{2\mu}\sqrt{\frac{\Delta h}{R_{кр}}}\right)\frac{\Delta h}{D_{кр}} + \frac{b_{р.з} - d_{кр}}{b_{р.з}}K_s^{и} \tag{36}$$

where: $К_{s\ кр}^{p}$- coefficient accounting for the non-uniformity of deformation across the width of the round pass during the rolling of a rhombus workpiece [4].

The application of the aforementioned recommendations for determining spread and lead values in pass design will enable greater precision in the manufacturing of high-quality parts, workpieces, and drop forgings.

4. Conclusions

A refined method for calculating the spread and lead indicators of aluminum alloy flow has been theoretically substantiated and developed. Unlike classical models, the proposed approach accounts for the dynamic change in deformation resistance directly within the deformation zone, allowing for a more accurate description of metal flow during hot rolling.

Optimal temperature regimes (250–350°C) for heating both the workpiece and the tool have been determined, ensuring a reduction in the temperature gradient and uniformity of plastic flow. It was established that when both the workpiece and the tool are heated to this temperature range, the spread and lead of the aluminum alloy flow remain stable and do not change.

Experimental verification of the developed method confirmed its high adequacy to real industrial processes. The application of the refined algorithm allowed for a reduction in calculation error to 5%, which significantly exceeds the accuracy of traditional models that exhibit substantial deviations of up to 40% when working with high-plasticity aluminum alloys.

The practical value of the results lies in the possibility of increasing the yield of usable rolled products by minimizing technological scrap and improving the precision of geometric dimensions. The obtained data are recommended for implementation in automated control systems and for use in designing new roll pass schemes, providing a significant economic effect and resource savings.

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АНАЛІЗ І РОЗРАХУНОК РОЗШИРЕННЯ І ВИПЕРЕДЖЕННЯ ТЕЧІЇ АЛЮМІНІЄВИХ СПЛАВІВ ПРИ ГАРЯЧОМУ ДЕФОРМУВАННІ

У даній роботі проведено поглиблений аналіз взаємозв'язку між кінематичними параметрами прокатування та фізико-механічними властивостями алюмінієвих сплавів. Вперше запропоновано метод уточненого розрахунку розширення та випередження, який, на відміну від існуючих методик, враховує динамічну зміну опору деформації в межах усього вогнища деформації. Це дозволило встановити більш точні функціональні залежності між ступенем обтиснення, швидкістю прокатування та напрямком течії металу в поздовжньому та поперечному напрямках. Особливу увагу приділено впливу реологічних властивостей матеріалу на нерівномірність розподілу швидкостей у контактних та внутрішніх шарах заготовки.

У роботі використано комплексний підхід, що поєднує теоретичний аналіз кінематики вогнища деформації та математичне моделювання процесів пластичної течії. Розрахункова частина базується на принципах механіки суцільних середовищ із врахуванням температурно-швидкісного фактору та контактних умов тертя, характерних для гарячого деформування алюмінієвих сплавів. Для верифікації отриманих даних проведено порівняльний аналіз із результатами експериментальних досліджень.

Доведено, що традиційні моделі розрахунку мають значну похибку при роботі з високопластичними алюмінієвими сплавами в умовах високих температур. Уточнений алгоритм розрахунку забезпечує високу збіжність із експериментальними даними (похибка мінімізована до 5%). Встановлено, що точне регулювання параметрів випередження при температурі нагріву і заготовки і інструменту 250-350°C, що дозволяє уникнути дефектів поверхні, таких як закочування та нерівномірність кромок, що критично важливо для прокатування деталей складного поперечного перерізу.

Впровадження розробленого методу у виробничий процес дозволяє значно підвищити точність геометричних розмірів готового прокату та стабілізувати процес налаштування станів. Це мінімізує обсяги технологічної обрізі та забезпечує раціональне використання дорогої сировини. Економічний ефект досягається за рахунок зниження енерговитрат на повторну переробку браку та суттєвого підвищення частки виходу придатного продукту. Результати дослідження можуть бути рекомендовані для використання проектно-конструкторськими бюро при розрахунку калібрування валків та розробці автоматизованих систем керування процесами прокатки.

Ключові слова: *алюмінієві сплави, заготовки, пластична деформація,, гаряче прокатування, розширення, випередження, технологічний процес.*

Ф. 36. Рис. 4. Літ. 7.

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