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Technology for Manufacturing Parts from Aluminium Alloys Using Hot Deformation

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Pressure treatment of metals includes the method developed by us for manufacturing billets from aluminium alloys by hot deformation. There are many methods of hot manufacturing of blanks from various materials; our proposed method of hot deformation of aluminium alloys involves heating not only the metal itself, but also the dies, in which the billet is to be melted for the required part. The essence of the method also consists in the fabrication of different-calibres' stamps depending on the desired part, which can be both symmetrical and complex ones with an elongated, bent axis, of various configurations, with a minimum of waste. The material consumption factor for this technology is of 0.15–0.3.

Key words: technological process, deformation, heat treatment, deformation drawing, annealing, aluminium alloys, smooth rolls, stamps, stressedly-deformed state, plasticity.

До оброблення металів тиском відноситься розроблена нами метода виготовлення заготівок із алюмінійових стопів гарячим деформуванням. Є багато методів гарячого виготовлення заготівок із різних матеріялів, та запропонована нами метода гарячого деформування алюмінійових стопів передбачає нагрів не тільки самого металу, а й штампів, в яких має виплавлятися заготівка під потрібний деталь. Суть методи також полягає у

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виготовленні різного калібру штампів в залежності від потрібного деталю, які можуть бути як симетричні, так і складні з витягнутою, зігнутою віссю, різної конфіґурації, з мінімумом відходів. Коефіцієнт витрати матеріялу за такою технологією складає 0,15–0,3.

Ключові слова: технологічний процес, деформація, термічне оброблення, деформаційне протягування, відпал, алюмінійові стопи, гладкі валки, штампи, напружено-деформований стан, пластичність.

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1. INTRODUCTION

Aluminium alloys have great potential in various industries due to their properties and structure. Lightness, corrosion resistance, and mechanical properties make them attractive for the production of a variety of parts used in aviation, automotive, agricultural machinery, shipbuilding, electronics, and other light and heavy industries. It is not insignificant that this is an expensive material, and it is desirable to use it with minimal costs. When processing these alloys, various processing technologies are used, which affect the structure and mechanical properties of the material and change it, which negatively affects the purpose of the part itself. We offer a method of hot deformation of aluminium alloys, which restores both the structure and mechanical properties of the manufactured workpiece, which is as close as possible to the dimensions and design of the finished part, requires a minimum of processing, and in some cases, even without additional mechanical processing. There are many methods of hot manufacturing of blanks from various materials; the proposed method of hot deformation of aluminium alloys involves heating not only the metal itself, but also the dies, in which the billet is to be melted, for the desired part. The essence of the method also consists in the production of stamps of different calibres, depending on the required part, which can be both simple and complex, of different configurations.

2. PRESENTATION OF THE MAIN RESEARCH MATERIAL

The results of theoretical studies of the flow of metal in the transition and stable zones during hot deformation of workpieces in the centre of deformation, taking into account the development of deformation over time, formed the basis of studies of the unevenness of deformation and the nature of the flow of metal depending on the ratio of the geometric shapes of the gauges. The results of the research were used in obtaining formulas for determining the expansion and advance during the deformation of blanks in smooth rolls and gauges of different systems [1].

Expansion Δb is defined as the difference in the width of the sample before and after deformation:

$$\Delta b = b_1 - b_0 , \quad (1)$$

where b_0 is the width of the sample before deformation [mm], b_1 is the sample width after deformation [mm].

The advance of S is determined by the formula

$$S = (l_1 - l_2)/l_2 \cdot 100\% , \quad (2)$$

where l_1 is the distance between the impressions of the cores on the workpiece [mm], l_2 is the distance between the impressions of the cores on the rolls [mm].

The metal pressure on the rolls was determined by the formula

$$P = 1 - (P_0 - P_1)/P_0 , \quad (3)$$

where P is relative pressure, P_0 is metal pressure on rolls with a temperature of 20°C [kg/mm^2], P_1 is metal pressure on rolls with a temperature of 50–450°C [kg/mm^2].

The technology of manufacturing parts from aluminium alloys by hot deformation for stamping includes: construction of a drawing of the workpiece; determination of the size of the initial workpiece; determination of the general coefficient of extraction on transitions and selection of the system of gauges; calculation of calibres and design of stamps on transitions; the choice of thermomechanical modes of deformation of blanks of a specific aluminium alloy; safety issues.

Thermomechanical modes of deformation should ensure sufficient plasticity, uniform structure and high mechanical properties [2, 3].

Table 1 shows data on the selection of thermomechanical modes of deformation of aluminium alloys [3].

When the blanks are deformed in the perpendicular direction of the axis, the permissible deformation values given in Table 1 should be reduced for aluminium alloys by 15–25% for one heating in order to avoid obtaining a coarse-grained structure, due to the processes of recrystallization, forging and stamping of aluminium alloys according to typical technologies [3].

When studying the main technological parameters of the deformation of billets from aluminium alloys according to the proposed method, comprehensive studies of the macro- and microstructure of samples cut from the deformed billet were carried out. Billets were made of AK6 alloy with dimensions ∅14×150 mm and were deformed in oval calibres, the dimensions of which are given in Table 2.

The manufactured blanks were thermally treated and subjected to comprehensive analysis. Mechanical tests were carried out on a break-

TABLE 1. Thermomechanical modes of deformation of aluminium alloys.

Alloy grade	Temperature interval of deformation, °C	Admissible degree of deformation, %	
		Casting workpiece	Pressed workpiece
AMn, AMg1, AMg2, AB AD31,	470–300	70	90
AD33, AD35, AK6, AD0, AD1, 01205	470–300	70	90
D1, D1ch, BD17, 1230 AK8	470–370	60	70
	450–350	–	60
D20, D21, 1201, AK4 AK4-1, K4-1ч	470–350	60	70
	430–320	–	60
AMg3, AMg4, AMg5 AMg5p, AMg6, B92	430–320	60	60
M40, B92c, 1915, 1913	430–300	–	50
B95, B95pch, B96C, B96Cpch, B96C3	430–350	60	60
	430–320	–	50
D19ch, BAD1 (1191), D16ch	470–350	60	60
	430–350	–	50

TABLE 2. Dimensions of oval gauges for deformation of workpieces from aluminium alloys with dimensions of ∅14×150 mm [3].

Axis ratio a	Calibre height h, mm	Calibre width b, mm	Calibre radius R, mm	Coefficient of elongation λ
2.0	9.3	18.65	11.70	1.45
2.4	8.3	19.9	11.95	1.55
2.8	7.1	20.1	12.00	1.65

ing machine with a nominal force of 20 000 N. The test results are shown in Table 3.

From Table 3, we can see that the hot deformation of the blanks increases the strength σ by 7.14% and the plasticity δ by 14.33% compared to the original bar.

As the process of hot deformation was mastered, regularity was confirmed: the blanks after deformation had a higher strength than the pressed bar. The improvement of the metal structure and the improvement of the mechanical properties of the workpieces can be explained as follows: the deformation is carried out in hot dies with gauges, the shape of which is close to the shape of the cross section of the final part. Differences of intersections along the gauge are selected by smooth radii [1].

This form of the tool ensures a sufficiently uniform deformation of the metal, creates a comprehensive crimping of the workpiece, as a re-

TABLE 3. Results of mechanical tests of samples after hot deformation [3].

Type of semi-finished product	σ, MPa	δ, %
Initial sample	380	16,0
Samples after deformation	405	22,0
-//-	415	22,0
-//-	415	18,0
-//-	425	24,0
-//-	427	22,0
-//-	420	22,0
-//-	420	18,0
-//-	430	18,0
-//-	420	20,0
-//-	430	20,0
-//-	420	20,0

TABLE 4. Sizes of calibres for hot deformation of billets from the AK6 alloy, ∅25×150 mm.

Oval calibre						Square calibre						
h, mm	b, mm	R, mm	m, mm	r, mm	F, mm^2	m, mm	h, mm	b, mm	c, mm	h', mm	r, mm	F, mm^2
7.9	41.8	57.5	1.0	3	214	1.0	15.2	16.7	11.8	16.7	1.8	137

sult of lateral pressure that approaches the final part. This increases the plasticity of the metal and allows only one deformation. High degrees of crimping ensure the penetration of deformation into the central zones of the workpiece, causing grinding, compaction and orientation of the grains in the direction of movement of the metal during processing.

In another series of experiments, workpieces made of AK6 alloy with dimensions of ∅25×150 mm were deformed according to the circle–oval–square system in calibres, the dimensions of which are given in Table 4 (refer with Fig. 1).

The deformed blanks were thermally treated according to the technology shown in Table 5. As a result of a visual inspection and analysis of the macrostructure of the deformed blanks, it was established that pinching, cracks, fibre pinching and other structural violations were not detected [4]. The results of mechanical tests of samples cut from rolled blanks are given in Table 5.

Features of Hot Deformation of Aluminium Alloy Parts. To calculate gauges and develop a technological process of deformation of blanks from aluminium alloys for subsequent stamping, it is necessary to know the peculiarities of stamping parts from these alloys [5–7].

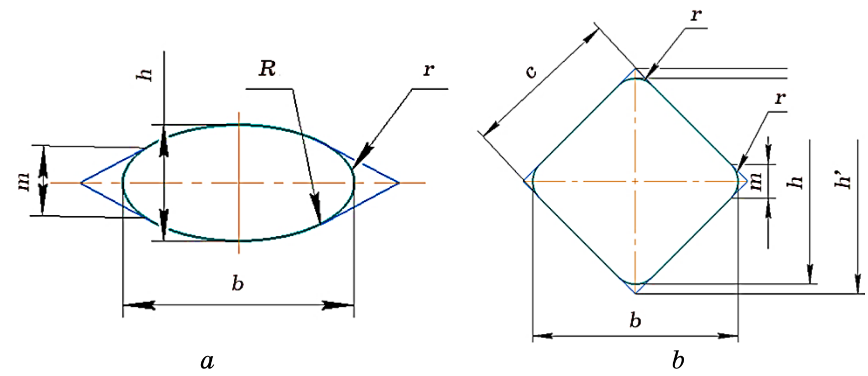


Fig. 1. Calibre sizes: *a*—oval, *b*—square.

TABLE 5. Technology of heat treatment of deformed billets from AK6 alloy, ∅25.

Type heating furnace	Type of heat treatment	Alloy	Temperature of the initial reference time, °C	Heat treatment temperature, °C	Exposure time	Cooling medium
PN-32	Hardening	AK6	500	505–252	50 min	Water
PN-32	Ageing			160–175	3.4–4 hrs	Air

1. The essence of hot deformation is the deformation of metal at low speeds at a uniform temperature of the stamped material, which is achieved as a result of the equality of the initial heating temperatures of the workpiece and the tool. During hot deformation, heat loss of the workpiece to the environment is excluded.

2. The possibility of deformation at low speeds and a constantly high temperature of the workpiece ensure high plastic properties of the processed materials, uniform deformation, and reduced specific stamping forces.

3. The increased plasticity of the stamped material allows you to stamp parts of a complex configuration with thin webs and high thin ribs in one pass.

4. Constant temperature stamping conditions, absence of tool temperature fluctuations, reduced stamping forces provide the possibility of stamping high-precision parts and a significant reduction in the volume of further mechanical processing.

5. Low loads on the stamps and stable temperature conditions of the stamps guarantee their high stability.

6. The high accuracy of the parts obtained by hot deformation causes increased requirements for the accuracy and cleanliness of the tooling and stamping equipment.

7. The production of parts by the method of hot deformation allows

you to reduce significantly the labour intensity of mechanical processing and the consumption of metal, which is expensive.

Requirements for Initial Preparation [8, 9]. For the production of blanks by hot deformation, blanks previously deformed by pressing, rolling or forging are used. The blanks loaded into the furnace for heating for deforming operations must not have surface defects: drains, cracks, burrs, *etc*. Defects must be removed by mechanical processing (turning).

Surface roughness after turning should correspond to alloys with high and medium technological plasticity $R_a = 6.3$ µm, and with reduced technological plasticity $R_a = 1.6$ µm. The imprint of the remaining centres on the ends of the workpieces made of alloys with high and medium technological plasticity after turning should be smoothed with sandpaper, and the ends of the workpieces with reduced plasticity should be sanded until the traces of the centres are completely removed, the edges should be rounded with a radius of 5–10 mm.

The surface of the workpieces loaded into the furnace must be clean and dry (without shavings, sand, soot). Moisture on the surface of the workpieces is not allowed.

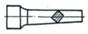
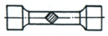
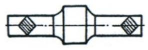
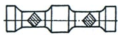
The initial material intended for cutting into dimensional blanks, in terms of structure and mechanical properties, must meet the requirements of the technical documentation in force [6].

Production of Profiles of Complex Cross-Section Using Hot Deformation Technology. The problem of manufacturing profiles of a complex cross-section from aluminium alloys is acute in the aviation industry and other branches of mechanical engineering. The lack of special equipment for pressing profiles from aluminium alloys of arbitrary cross-section at machine-building plants (especially at enterprises of small-scale production) poses the task of researching the possibility of manufacturing profiles by other methods, since their production by mechanical processing is associated with significant labour costs and increased consumption of metal.

We propose to divide the typical workpieces proposed by us into groups in Table 6, the basis of which classification includes typical workpieces and profiles, their configuration and technological possibilities of obtaining them on the equipment proposed by us.

A review of literature sources showed a lack of recommendations for the use of rolling and rolling to obtain profiles of complex cross-section from aluminium alloys [10]. Along with the lack of a universal method of calculating gauges for the manufacture of profiles of a complex shape [11–13], it also turned out to be limited data on the calibration of rolls of already mastered profiles. The existing methods cover issues specific only to certain groups of profiles (channel, angle, I-beam) and are based on empirical, semi-empirical methods, as well as methods based on various techniques.

TABLE 6. Classification of typical blanks for production by hot deformation.

I group	Blanks with one thickening at the end	
II group	Blanks with two thickenings at the ends	
III group	Blanks with one thickening in the middle	
IV group	Blanks with three thickenings	
V group	Workpieces with a curved axis	

Some authors [11–14] recommend, when calculating gauges, to develop simultaneously several calibration options in order to establish the best of them through successive tests. They indicate that the calibration of profiles of arbitrary cross-section should be accompanied by systematic tests of designed gauges, making the necessary corrections based on the results of experiments.

Due to the fact that the existing methods of calculating the calibres of steel profiles do not allow to unambiguously solve the question of the necessary and sufficient number of calibres, we proposed to take as a basis the dimensions of the calibres described in Ref. [3] (Fig. 2), and conduct experiments on the production of a steam pad, on the proposed equipment in rolls ∅160 mm with a frequency of their rotation of 12 min^{-1} according to the 'pre-cleaning–cleaning' calibre scheme. The overall extraction coefficient λ was of 2.82 (in the pre-clean gauge, 1.92, and in the clean, 1.46); Fig. 3. In addition, on forging rolls of the C1335 model in rolls of ∅320 mm with a rotation frequency of 26 min^{-1}, which have room temperature, for conducting experiments, workpieces from aluminium alloys AK4-1 and AK6 with dimensions ∅25×130 mm were used.

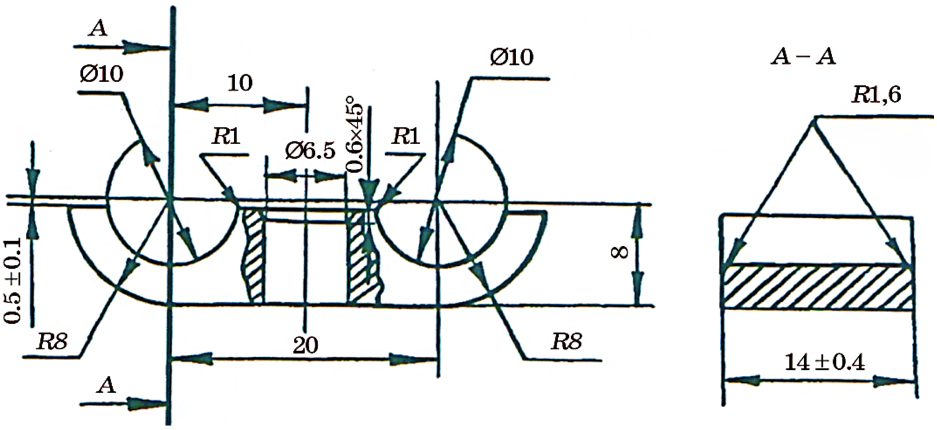


Fig. 2. Scheme of the calibre of the paired pads [3].

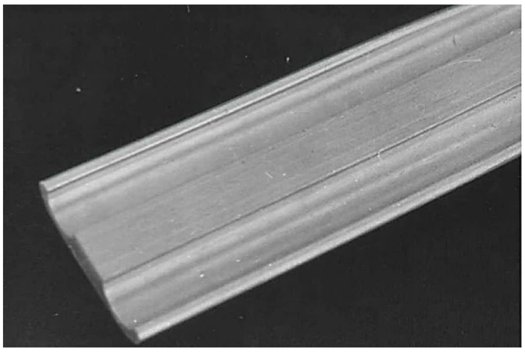


Fig. 3. A sample of the manufactured Paired Pads.

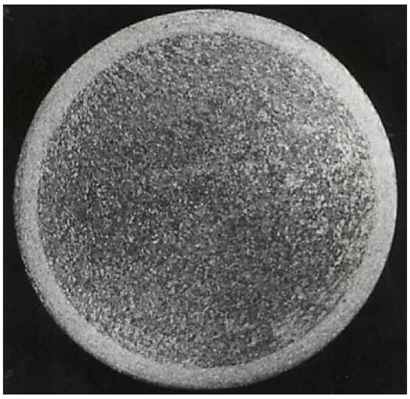


Fig. 4. Macrostructure of the primary workpiece with a large crystalline rim.

The heating temperature of the blanks and dies was of 470°C. Initial uneven structure (refer with Fig. 4) workpieces in the process of deformation have improved significantly. A visual inspection and analysis of the macrostructure is presented in Fig. 5 defects were not detected. The block profile has a uniform fine-grained structure along the length and width of the deformed part of the workpiece and meets the requirements of the technical documentation.

Table 7 shows the technical characteristics of the equipment and the technological parameters, at which the pad profile was manufactured, from which it can be seen that, for the manufacture of a pad in conditions of hot deformation, equipment of much less effort and dimensions is required, that allows to reduce energy consumption, reduce the labour intensity of manufacturing a part and the cost of workpieces.

The nature of the dependence of the expansion on the temperature of heating the stamps in the range of 20–250°C (Fig. 6) can be explained as follows. At the temperature of the stamps of 20°C and degrees of

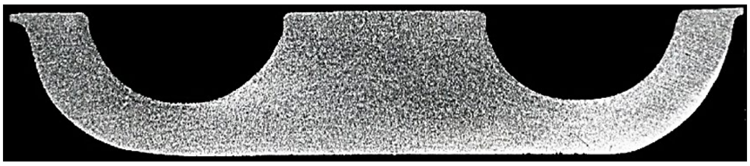


Fig. 5. Cross-section of the two-pass calibration profile of a paired pad.

TABLE 7. Comparative technical characteristics of equipment and technological parameters.

No.	Characteristic	Equipment	
		Rollers for forging C1335	Equipment for hot deformation
1	Drive power [kW]	80	7
2	Roll rotation frequency [min^{-1}]	26	12
3	Diameter of rollers [mm]	320	160
4	Dimensions for setting stamps [mm]	160	80
5	Stamp sizes [mm]:		
	first transition	92×80	50×40
	second transition	92×80	45×40
6	Central angle [α°]	180	180
7	Temperature of workpieces [°C]	470	470
8	Temperature of rolling dies [°C]	20	470

deformation of 30, 40, 50%, the contact area of contact between the metal and the stamps is small, taking into account the rolling of a round workpiece ∅14 mm. At the same time, the axial compressive stresses directed along the centre of deformation are insignificant compared to the compressive stresses acting in the transverse direction, therefore, an increase in expansion is observed. A decrease in expansion with an increase in the heating temperature of the rolling dies occurs due to the flow of strengthening processes and an increase in the plasticity of the processed metal.

In the heating temperature range of the rolling dies of 250–350°C at a constant degree of deformation, the expansion practically does not change, and the change in the degree of deformation changes the absolute values of the expansion by 15, 26, 37% relative to the initial cross section of the deforming blanks, respectively, with degrees of deformation 30, 40 and 50%. This occurs as a result of achieving equality of axial compressive stress directed along and across the centre of deformation, as well as equality of displaced volumes in these directions.

With an increase in the heating temperature of the stamps to 450°C and blanks with degrees of deformation of 30, 40 and 50%, the value of expansion relative to the initial cross-section of the blank decreases and amounts to 12.2, 23.6, 33%, respectively. The decrease in expansion occurs due to an increase in axial compressive stress directed along the centre of deformation, a more complete flow of strengthening processes, and the absence of zones of difficult deformation.

The analysis of expansion changes showed that with an increase in the heating temperature of the stamps, the expansion values decrease. Thus, the values of expansion obtained at the temperature of heating the dies to $t_b = 250$ and 450°C at deformation $\varepsilon = 30\%$ decrease in relation to the expansion obtained during rolling of blanks in dies with a temperature of 20°C by 37 and 67.2%, respectively [15]. The decrease in expansion at $t_b = 450$°C relative to $t_b = 250$°C is of 22%.

Similarly, the analysis of the change in expansion values during rolling of blanks at degrees of deformation of 40, 50% and other equal conditions showed that the expansion decreases by 15.4 and 27.3% ($\varepsilon = 40\%$), 13 and 26.45% ($\varepsilon = 50\%$). The decrease in expansion at $t_b = 450$°C relative to $t_b = 250$°C is of 10.3% ($\varepsilon = 40\%$), 11.8% ($\varepsilon = 50\%$).

Analysing Fig. 6, it can be seen that the change in the degree of deformation from 30 to 50% increases the value of the expansion, without changing the nature of their dependence on the temperature of heating the dies. It was noted above that with an increase in the degree of deformation, the volume of the metal in width and, therefore, the expansion, other things being equal, increase.

Figure 7 shows the macrostructure of the longitudinal cross-section of billets made of AK6 alloy in smooth dies in one pass at a temperature of billets and dies of 470°C, degrees of deformation 40 and 50%. Conducted comprehensive studies (macro-, microstructures, and mechanical properties) of the quality of rolled blanks, in hot conditions, met the requirements of the technical documentation.

Analysing Table 3 and Fig. 7, it can be seen that when rolling workpieces with dimensions $\varnothing 14\times 150$ mm at a temperature of 450°C, the relative pressure of the metal on the R_v rolls decreases with an increase in the heating temperature of the dies, and, most intensely, with an increase in the degree of deformation [16].

Thus, with an increase in the heating temperature of the stamps to 250, 350 and 450°C, the pressure on the rolls decreases in comparison with the pressure values during the deformation of the blanks in the stamps with a temperature of 20°C and a degree of deformation of 30, 40, 50%, respectively, by: 250°C—62.45%, 54%, 45%; 350°C—55.8%, 47.5%, 38.73%; 450°C—53.3%, 46.5%, 38.2%.

In the temperature range of 350–450°C, the metal pressure on the rolls at different degrees of deformation changes slightly, and when the dies reach temperatures of 400°C and above, it almost stabilizes, and an increase in the degree of deformation affects only the absolute values of the relative pressure P_v (Fig. 8).

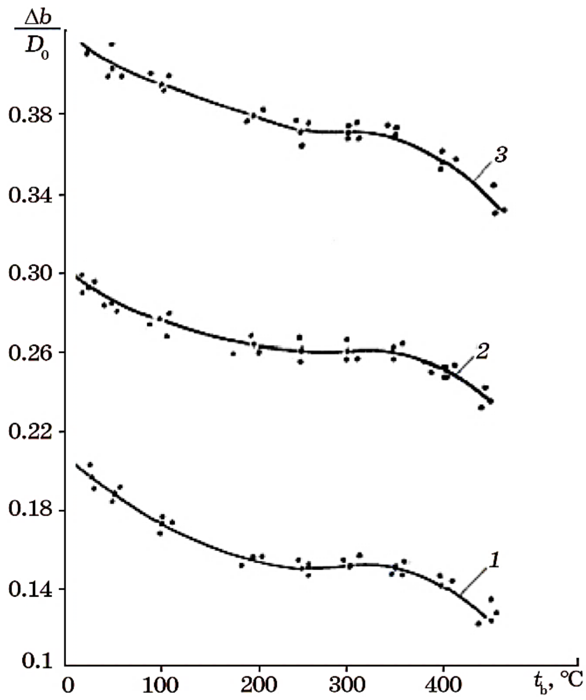


Fig. 6. Dependence of expansion on the degree of deformation and heating temperature of rolling dies (degree of deformation: *1*—30%, *2*—40%, *3*—50%; heating temperature of blanks 450°C).

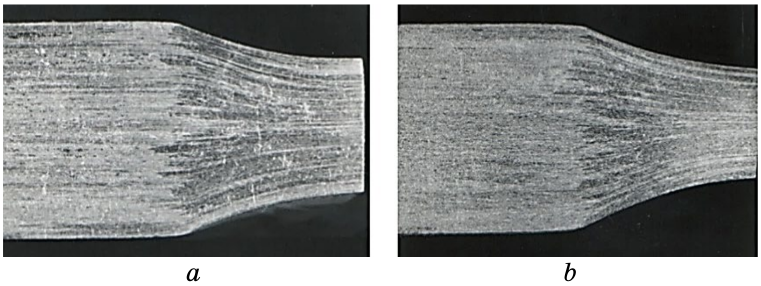


Fig. 7. Macrostructure of longitudinal sections of rolled blanks in smooth rolls. Alloy AK6, ∅14×150mm. Temperature of blanks and stamps—470°C: *a*—degree of deformation of 40%, *b*—degree of deformation of 50%.

Analysis of the experimental data presented in Fig. 8 shows that, during the rolling of blanks on forging rolls, in hot conditions, the metal pressure on the rolls decreases with the increase in the heating temperature of the dies, most intensively in the temperature range of 20–350°C. Further heating of the stamps does not lead to a significant

TABLE 8. The value of the relative pressure P_v depending on the temperature heating of stamps t_b and degree of deformation ε.

Item No.	ε = 30%		ε = 40%		ε = 50%	
	t_b, °C	P_v	t_b, °C	P_v	t_b, °C	P_v
1	20	0.4	20	0.5083	20	0.6664
2	250	0.2498	250	0.2747	250	0.3
3	300	0.2365	300	0.2498	300	0.2664
4	350	0.2232	350	0.2415	350	0.2581
5	400	0.2166	400	0.2365	400	0.2548
6	450	0.2133	450	0.2365	450	0.2548

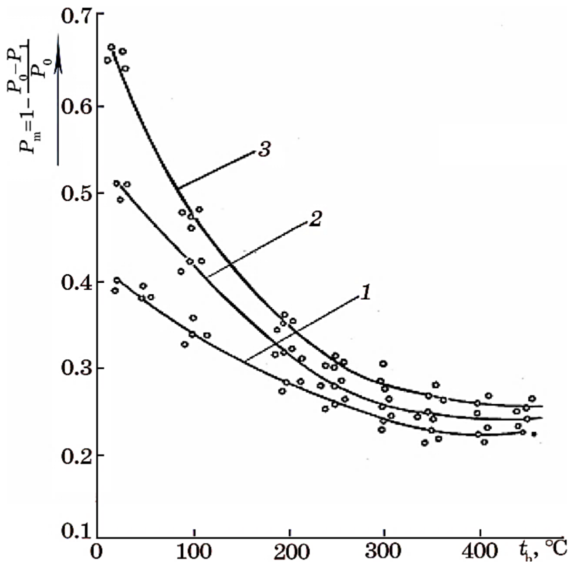


Fig. 8. Addiction the relative pressure of the metal for rolling from the temperature of heating the dies and the degree of deformation: *1*—30%, *2*—40%, *3*—50%. The heating temperature of the blanks is of 450°C.

decrease in pressure and is impractical, because it leads to additional energy consumption. In addition, the appearance of scale on the surface of the stamps is observed.

In another series of experiments, workpieces from the abovementioned alloys with dimensions of ∅14, 18, 20, 25×150 mm, electric resistance heated in a chamber furnace to temperatures of 300, 350, 400, 450, 470+10°C were rolled in smooth dies, which were heated sequentially to temperatures of 20, 50, 100, 150, 200, 250, 300, 350, 400, 470°C. The blanks were rolled with degrees of deformation of 30 and 40%. The results of the experimental data are presented in Figs. 9, 10.

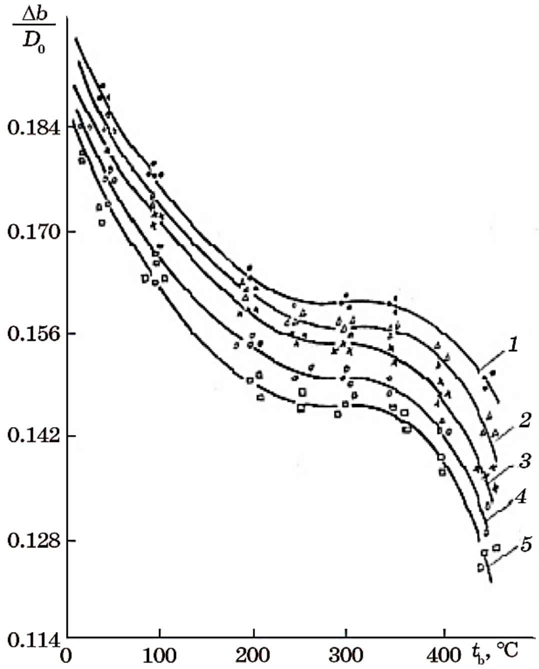


Fig. 9. Dependence of expansion on the heating temperature of blanks and stamps at a degree of deformation of 30% workpiece heating temperature: *1*—300°C, *2*—350°C, *3*—400°C, *4*—450°C, *5*—470°C.

Analysis of the experimental data presented in Figs. 9, 10 shows that, with an increase in the heating temperature of the blanks and stamps, the expansion decreases due to the strengthening processes. In addition, it should be noted that in the temperature range of heating stamps 250–350°C, the expansion at a constant degree of deformation (similarly presented in Fig. 10) practically does not change, and a change in the degree of deformation leads to a change in its absolute values.

Figure 11 shows the macrostructure of the longitudinal and transverse sections of rolled blanks made of AK6 alloy with dimensions ∅14×150 mm, corresponding to the requirements of the technical documentation. Rolling was carried out at temperatures of blanks and dies equal to 450°C with a degree of deformation of 50%.

3. CONCLUSION

Conducted experiments on the example of the production of a profile of a paired pads showed that the production of profiles with a complex cross-section is economically profitable to produce on the equipment for hot deformation proposed by us, since the equipment is used with

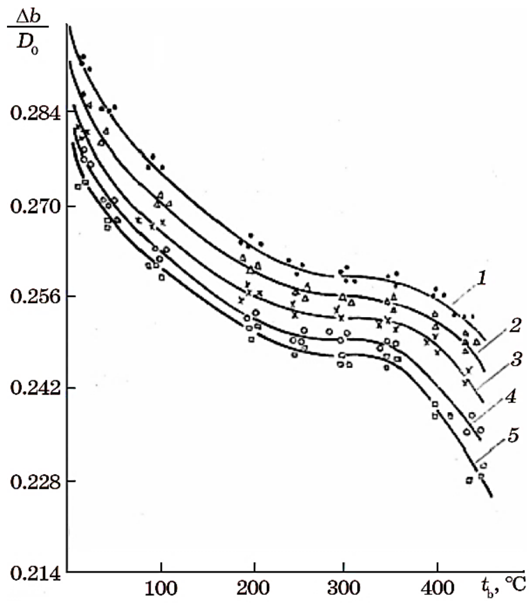


Fig. 10. Dependence of expansion on the heating temperature of blanks and stamps at a degree of deformation of 40% workpiece heating temperature: *1*—300°C, *2*—350°C, *3*—400°C, *4*—450°C, *5*—470°C.

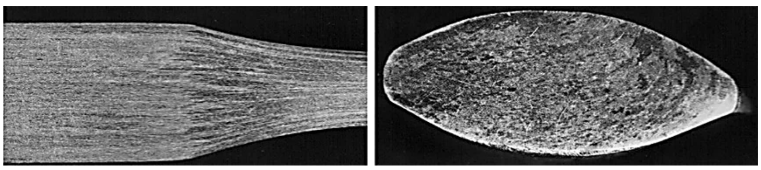


Fig. 11. Macrostructure of the longitudinal (*a*) and transverse (*b*) cross-sections of the rolled blank in oval gauge: AK6 alloy, ∅14×150; degree of deformation—50%; the temperature of blanks and stamps is of 450°C.

less effort and dimensions, due to the improvement of plasticity. In addition, the production cost of pads is reduced, due to decrease in the labour-intensiveness of mechanical processing, the reduction of the cost of the labour-intensive production of stamps, and the reduction of energy consumption. The quality of the structure and the mechanical properties of the manufactured workpiece are improving.

AUTHORS' CONTRIBUTIONS

L. V. Shvets developed the concept of the hot deformation technology for aluminium alloys, participated in planning the experiments, analysed the obtained results, and contributed to the interpretation of the mechanical and structural properties. K. V. Chmykh conducted experimental studies of hot deformation processes, performed mechanical testing of the samples, and processed the experimental data. O. O. Trukhanska carried out analysis of the stressed–deformed state, participated in the investigation of macro- and microstructures, and contributed to the discussion of the results. A. A. Shtuts participated in the development of technological parameters, assisted in experimental work, and contributed to the preparation of figures and tables. M. A. Kolisnyk supervised the research, formulated the main methodological and technological approaches, coordinated the study, and wrote the manuscript with contributions from all authors. All authors reviewed and approved the final version of the manuscript.

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