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Experimental Study of Energy-Power Parameters of Billet Rolling of Compressor Blades of Aircraft Engines

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The article presents experimental studies to determine the force and torque during die rolling of blades' billets of steel 14X17H2-Ш in the industrial mill of 'Motor Sich' JSC with different lubricants and conditions of metal sticking on the rolls. Experimental results confirm the effect of lubrication on the energy-power parameters of the process. However, the reduction in rolling force is not always accompanied by the reduction in metal sticking to the rolls. A more effective lubricant with good shielding properties is the barium chloride melt with relatively low roll pressures (of 520–570 kN) and a clean, defect-free metal surface. Analysis of the effect of the force and torque rolling shows that, during the rolling process of one period with the increase and decrease of reduction for different blade billet designs, the distribution of contact normal pressures along the length of the strain zone at each point of time changes that affects the force and torque. Experimental data show that the distribution of contact pressures during die rolling is determined by reduction, contact friction, through forward motion, as well as factors related to the non-uniformity of plastic strain along the length and height of the strip. The effect of shear strain can be used during designing the technology and shape of workpieces for compressor blades.

Key words: blade, aircraft engine, energy-power parameters, rolling, billets.

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У статті наведено експериментальні дослідження з визначення сили та моменту під час періодичного вальцювання заготовок лопаток із криці 14Х17Н2-Ш на промисловому стані АТ «Мотор Січ» з різними змащеннями й умовами налипання металу на валки. Результати експерименту підтвердили вплив мастила на енергосилові параметри процесу. Однак пониження сили вальцювання не завжди супроводжувалося зменшенням налипання металу на валки. Більш ефективним мастилом, що має хороші екранувальні властивості, є розтоп хлористого Барію, за якого є порівняно невисокі тиски на валки (520–570 кН) і чиста, без дефектів поверхня металу. Аналіза впливу сили та моменту вальцювання показує, що в процесі вальцювання одного періоду з наростанням і зменшенням обтиску для різних конструкцій заготовок лопаток відбувається зміна розподілу контактних нормальних тисків по довжині осередку деформації в кожен момент часу, що впливає на силу та момент. З експериментальних даних маємо, що розподіл контактних тисків під час періодичного плющення визначається обтисненням, контактним тертям, через випередження, а також чинниками, пов'язаними з нерівномірністю пластичної деформації за довжиною та висотою смуги. Ефект впливу зсувних деформацій слід використовувати під час проєктування технології та форми заготовок для компресорних лопаток.

Ключові слова: лопатка, авіяційний двигун, енергосилові параметри, вальцювання, заготовка.

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1. INTRODUCTION

High precision and strict requirements to the surface quality and physical and mechanical properties of the material in the surface layer, extensive use of heat-resistant and light alloys, and the use of the latest methods of workpieces and parts production are modern features of aircraft engine construction.

The quality of products and the cost of their production are key factors determining the competitiveness of enterprises. The geometric accuracy achieved largely determines the quality of products. Increased requirements for the performance characteristics of gas turbine engine lead to increased requirements for the accuracy of its parts by 20–40%. At the same time, economic feasibility limits the allowable increase in the cost of manufacturing an engine. Cost reduction for series production is possible by increasing labour productivity, which can be achieved by improving technological processes and the use of modern high-performance equipment [1–5].

Modern aircraft engines are highly stressed thermal machines in which complex aerodynamic processes take place. To implement these processes, it is necessary to have parts with complex surfaces. Such parts include compressor and turbine blades, impellers, monocoils, *etc*.

In gas turbine engines, much attention is paid to the production of compressor blades. This part is the most massive part of a gas turbine engine, and its geometry determines the performance of the gas turbine engine as a whole. The perfection of compressor blades aerodynamic process is determined by the level of profiling during design and the accuracy of their manufacturing achieved in production [6–9]. The resulting geometry of compressor blades is determined by the following factors: accuracy of transfer of theoretical surface model to the forming equipment, its technological capabilities, accuracy and rigidity of used tooling, perfection of the technological process of manufacturing and measuring the part.

Requirements for the accuracy of compressor blade airfoils are constantly increasing. The specified accuracy of gas turbine engine compressor blades production is achieved by a step-by-step machining of workpieces. Each subsequent machining step is characterized by a gradual increase in accuracy, with a decrease in the allowed tolerance and a decrease in the material removal rate. Machining errors in the initial stages lead to an increase in the volume of unevenly removed material in the final stages, which entails a decrease in the overall performance of gas turbine engine blades manufacturing.

Increase in overall productivity can be achieved by integrated control of dimensional processing parameters of forming operations in the manufacturing process of gas turbine engine compressor blades. Adjustment of dimensional parameters of forming operations will allow compensating machining errors and redistributing the volume of removed material from the final stages to the initial ones. The amount of time-consuming manual finishing of gas turbine engine compressor blades can be eliminated by using robotic complexes.

Alloy steels and titanium alloys are mainly used to manufacture compressor blades [10, 11]. The use of aluminium alloys is limited, mainly due to their low heat resistance.

The operating conditions of compressor blades determine the requirements for the materials from which they are made. The blades shall remain functional at temperatures up to 800°C, as well as have increased corrosion resistance. A characteristic property of heat-resistant corrosion-resistant steels and alloys is resistance to corrosion, which is mainly due to chromium in their composition. The property of chromium to increase corrosion resistance is associated with its ability to form a protective impermeable oxide layer on the metal surface, insoluble in aggressive corrosive media.

Compressor blade airfoil is relatively thin with a significant difference in thickness from the end section to the root section, as well as small curvature (large radius of the circle inscribed in the cross-sectional profile).

Considering methods and technological processes of compressor blades production, it should be noted that similar blades, as a rule, at different factories are produced by different methods with different means, significantly differ in technical and economic indicators (in labour input, technological cost, reduced costs) and production technology [12–15]. This is a significant disadvantage that shall be eliminated based on process typification, in which blades similar in their design and technological characteristics should be processed using a single process that provides the best technical and economic performance.

Even with small part manufacturing programs, nowadays to obtain such workpieces following methods of metal forming are used: hot and cold forging, pressing, drawing, longitudinal die rolling and others. They ensure a certain arrangement of fibres and the necessary degrees of strain during further processing, as well as the required physical and mechanical properties.

When developing the technology for manufacturing new products and improving the technology already in use, it is advisable to use only progressive high-performance and efficient processes that ensure, to a large extent, the further development of engine construction.

In this case, the choice of technological scheme and the development of processes to produce critical parts should be linked to the serial nature of the products, since depending on this may be recommended different methods of production. In any case, they shall be simple and cost-effective in the manufacture of equipment and preparation for production.

At present, there is still the matter of optimal technological scheme to produce complex products, as evidenced by the variety of applied schemes, including various methods of production (machining on metal-cutting machines, stamping, extrusion, rolling, and longitudinal die rolling) [16–19].

Longitudinal die rolling is currently a fairly well mastered process of pre-forming workpieces of gas turbine engine blades, first developed at 'Motor Sich' JSC (Zaporizhzhya) [20].

In this regard, the purpose of the work is to improve the accuracy of aircraft engine blades by studying the energy-power parameters of blades billet rolling.

2. EXPERIMENTAL

Experimental studies were conducted at the industrial mill 330 of 'Motor Sich' JSC (Fig. 1). Mill roll housing is rigid, closed type, cast. The rolls are pivotally connected to the shafts of pinion stand, made in one housing with a cylindrical four-stage gearbox with a gear ratio of 0.042.

Working tool for plastic strain was prefabricated rolls of

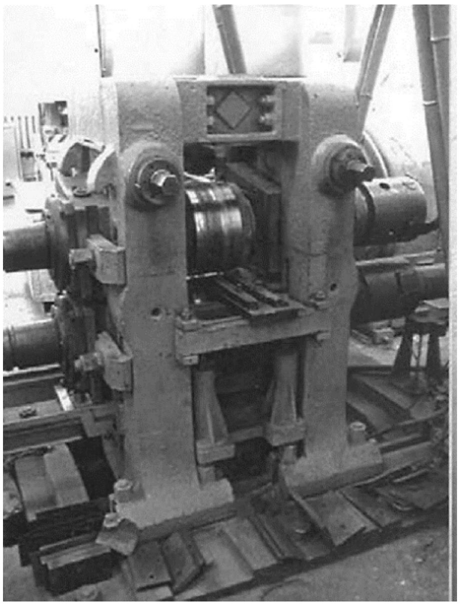

Fig. 1. Industrial mill 330.

4Х4М2ВФС steel with hardness after heat treatment *HRC* 50–54. Hydraulic support is used to calibrate the rolls axes of mill 330. The total pressure on the rolls was measured by rod-type load cells, which were installed under the lower chokes of the mill stands. Sensors with resistance of 200 Ω in full bridge circuit were used to measure the torque. Current collection during spindle rotation was performed by means of a sliding current collector, which was installed on the neck of the universal spindle fastened with two clamps.

The need for experimental determination of the force and rolling torque arose in determining the output thickness of the blade airfoil during die rolling of blades billets of steel 14Х17Н2-Ш with different lubricants and conditions of metal sticking on the rolls.

3. RESULTS AND DISCUSSION

Figure 2 shows typical oscillograms of force and torque.

Table 1 shows experimental data of process parameters of die rolling of blades from steel 14Х17Н2-Ш with different lubricants. Based on these data, the graphs of energy-power parameters distribution over the length of one period are plotted.

The following symbols are used in this table: *B*—heating in a barium bath, *P*—sample without lubrication, rolls lubrication—polymerized cotton oil (PCM) and water, *S*—sample glass 4-P, enamel EV-55, glass

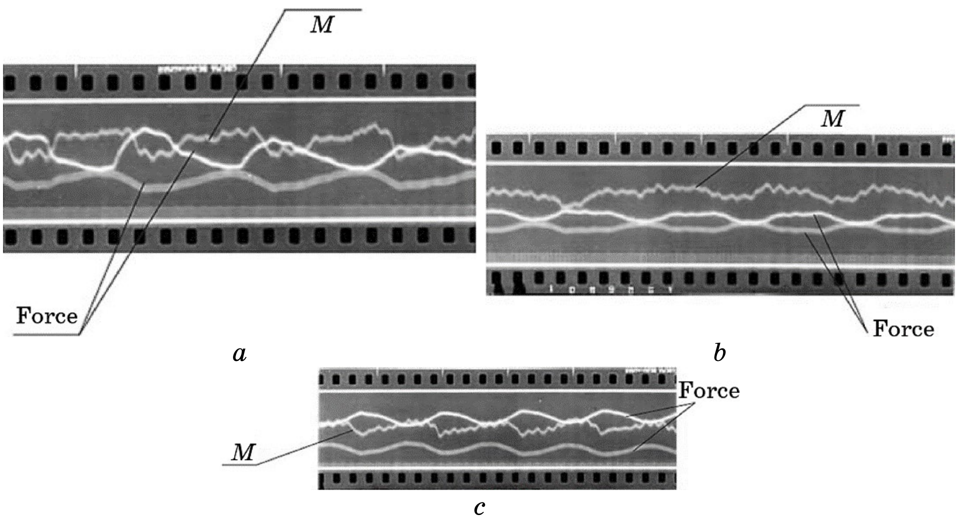

Fig. 2. Typical oscillograms of rolling force and torque during rolling of blades billets of IV stage of AI-20 engine blades from steel 14X17H2-Ш with different lubricants: heating in $BaCl_2$ salt (*a*), mixture: glass 4-P, 600 and enamel EV-55 (*b*), enamel EVT-24 (*c*).

600, rolls—without lubrication, *E*—sample protective-lubricating coating (enamel EVT-24), rolls—without lubrication.

The experimental results (Table 1) show that the energy-power parameters of the rolling process respond to lubrication. However, the reduction in rolling force was not always accompanied by a reduction in metal sticking to the rolls. A more effective lubricant with good shielding properties is the barium chloride melt with relatively low roll pressures (of 520–570 kN) and a clean, defect-free metal surface.

Figure 3 shows distributions of force and strain moment along the strip length during die rolling of blade blanks for different lubricant grades.

Figure 4 shows diagrams of forces and moments of strain distribution during die rolling of blades blanks of stage I of AI-25 compressor made of BT-8 alloy, which show that the distribution of energy-power parameters along the length of one strip period is uneven and varies over a wide range. The minimum value is in the area of small strains (blade shank), and the maximum is in the area of large strains (end of blade airfoil), where the shift of rolling force and moment distribution relative to each other in the direction of the minimum compressions of the latter parameter is observed. There shall be a correspondence between the force and the torque, because

$$Mkp = Pa = Pl_d\Psi, \quad (1)$$

TABLE 1. Parameters of blade billets rolling from steel 14X17H2-Ш with different lubricants.

No. of lubricant type	Lubricant	Period measurement location on the strip	Relative reduction	Average forward flow S, %	Reduction ratio	Maximum energy and power rolling parameters		
						Force P_1/P_2, kN	Total force, kN	Rolling torque, kN·m
1	B	Beginning	84.9	7.5	2.2	223–302	525	18.0
		Middle	82.4	5.9		251–322	573	18.0
		End	84.3	6.6		248–298	546	18.0
12	P	Beginning	81.0	4.8	1.9	169–384	553	22.0
		Middle	81.6	5.3		175–434	609	24.0
		End	83.6	5.5		134–335	469	19.0
15	S	Beginning	84.8	8.1	2.1	221–306	527	12.0
		Middle	84.3	9.7		239–342	581	12.0
		End	83.6	7.5		232–320	552	12.0
16	E	Beginning	87.8	5.1	2.3	173–242	415	16.0
		Middle	87.8	5.5		181–250	431	15.0
		End	84.3	6.2		228–329	557	20.0

where a—the rolling moment arm, Ψ—the rolling moment arm ratio.

To a certain extent, the torque shall repeat the distribution of the rolling force over the length of one period. Although this correspondence mainly takes place, it is clear from the experimental data that in the place of the minimum values of forces, distribution moments in this area increases sharply and such correspondence is not observed. Let us first consider the measurable process parameters. Force charac-

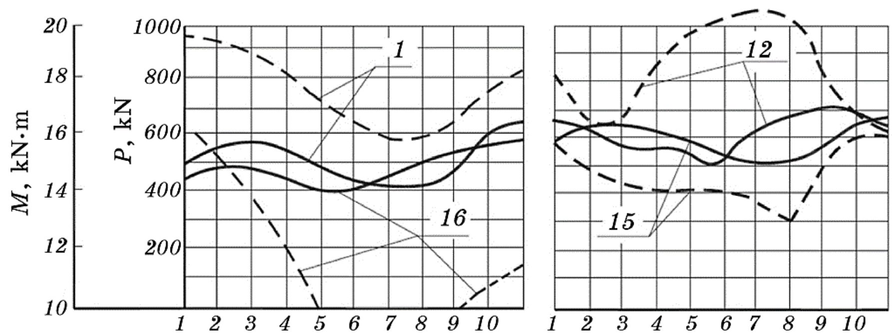

Fig. 3. Distribution of energy-power parameters during rolling of blades blanks from steel 14X17H2-Ш with different lubricants over the length of one period (the number of curves corresponds to the number in Table 1); solid line—rolling force, dashed line—rolling moment.

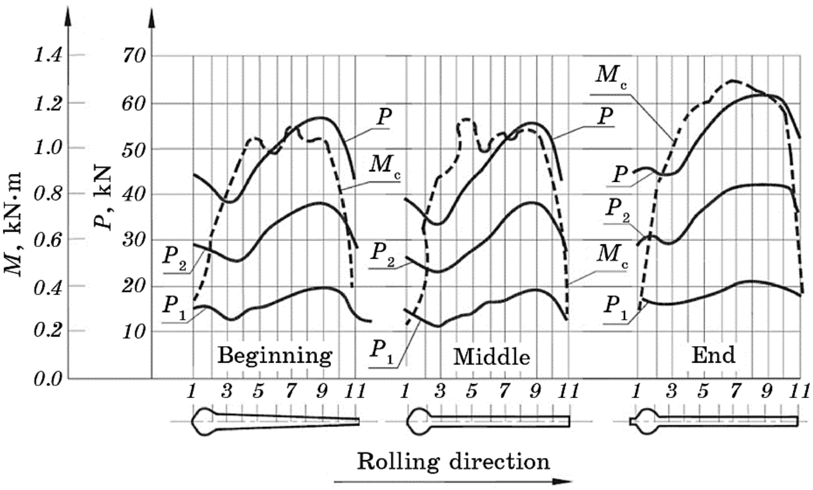

Fig. 4. Force and strain moment distributions during rolling of blades blanks of I stage of AI-25 compressor made of BT-8 alloy.

terizes the impact of the tool on the strained metal. The rolling torque is an energy characteristic of the process (the dimensionality of work and torque are the same). To a greater extent, torque responds to a change in work than to a change in force. When rolling without local anomalies, the force distribution diagram, as well as the moment diagram, shall not have a dip in sections 2 and 3 (Fig. 4), but increase towards the increase in the crimping along the airfoil length. If such anomalies exist, it is necessary to determine the physics of this phenomenon. Let us subject this inconsistency in the experimental data in the sections of transition from the tail part to the thin-walled, airfoil part of the profile to a more detailed analysis.

For the blade blank structures, when studying the metal flow in the transition zones from the tail section to the thin-walled airfoil section (sections 2, 3; see Fig. 4), intense shear strains are observed. Surface strains in this zone are maximal. In the same sections, we experimentally recorded a decrease in the rolling force; there was a dip in the force diagram (Fig. 4). Consequently, in the zone of intense shear strain, the rolling force decreases its value. Earlier, when considering the effect of plastic strain, the effect of longitudinal and transverse shear on the force and torque of rolling was noted. The peculiarity of the local plastic strain presented above is the appearance of symmetric intense shear along the section height, without overlapping zones. This fits into the general scheme of plastic strain effects due to strain shifts in the centre of profile formation.

Another feature of the strain and force state of the thin (airfoil) part of the blade profile is the coincidence of two more remarkable points.

In sections 8, 9, 10, the section of maximum rolling forces (Fig. 4) surface strains are minimal or absent at all. If we accept the thesis that under conditions of non-uniform reduction the metal moves from areas of higher pressure to areas of lower pressure and higher reduction to areas of lower pressure, it becomes obvious that the area of maximum pressures is the interface zone of metal flow. This is confirmed by experimental data on the study of surface strain. In the metal flow interface, the sign of longitudinal strain changes. Therefore, there is no displacement and strain in this area. Such metal flow, as shown above, forms the contours of lagging in the zone of decreasing reduction and forward in the zone of increasing reduction, which was recorded by theoretical and experimental studies of the die rolling process.

As a result, we managed to link into a single scheme the process of forming a 'thin-walled' profile of variable thickness, where the strained and stressed states of the strip during die rolling are connected in a certain way. In the transition from a section with a greater thickness to a smaller one, in the lagging contour zone there appear intensive shear strains along the height of the thin-walled part of the profile, reducing the rolling force. At the same time, vertical reduction in this part of the transition increases sharply, similar to the rolling torque growth diagram. The observed dip in rolling force diagram is explained by the effect associated with an increase in plastic shear. On the opposite side, in the zone of maximum forces, the interface line of metal flow is outlined, in relation to that the contours of lag and forward are formed.

Figure 5 shows distribution of rolling force and torque over the period length for blades of IV stage of AI-20 compressor from steel 14X17H2-Ш. The displacement of force and moment distribution diagrams with respect to each other is even more evident. The maximum torque shifts to the transition area from minimum reductions to maximum and minimum rolling force values. To some extent, the torque repeats the distribution of relative vertical reduction along the length of the profile. In the middle and at the end of the strip period there is a dip in the torque diagram in the area of high force values, where the interface zone of the metal flow is probably located.

Longitudinal plastic strains in this zone are minimal and, obviously, contact specific frictional forces, determined by longitudinal relative slip, are insignificant. This leads to a decrease in the friction ratio and, consequently, in the rolling torque, although the value of forces at the end of the rolling increases. The length of lag zone also affects the rolling torque: the larger it is, the higher the rolling torque is. In the reduction zone, which takes place when rolling a thin part of the profile, the lag zone is determinative. Consequently, the rolling torque in this part will be maximum, and the rolling force has not yet reached its maximum value. In the zone of increasing reduction, the defining zone

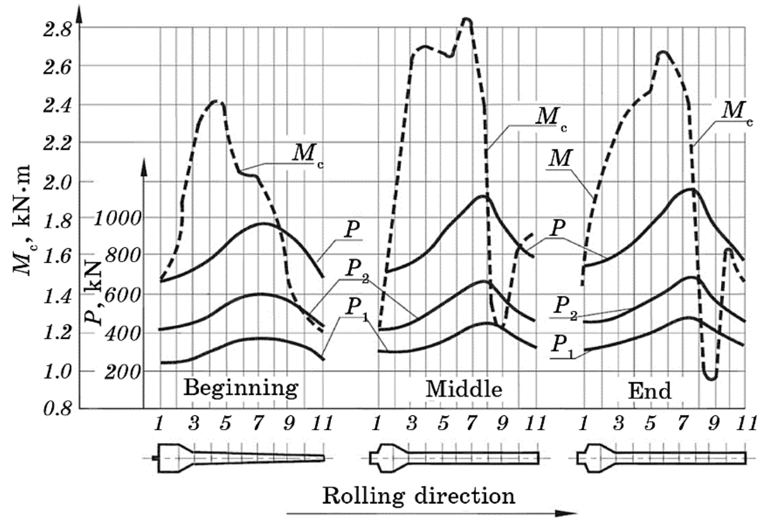

Fig. 5. Distribution of rolling force (P) and strain moment (M) along the length of one period of blades blanks of IV stage of AI-20 made of steel 14X17H2-Ш beginning, middle, end—distribution of periods along the length of the strip.

is the forward slip zone. Occurrence of forward zone, according to Bayukov's formula, leads to a decrease in torque, which is reflected in the torque diagram in Fig. 5. The rolling torque decreased significantly in magnitude, which led to a dip in the torque diagram.

Figure 6 shows the distribution of force and rolling torque along the length of one period of blades of X stage of compressor blades of AI-20 product from steel 14X17H2-Ш.

Workpiece shape is sharply different from the shape of previous products. There are two thickenings at its ends. In addition, the thickness of workpiece in the area of sections 8–10 is much greater than the thickness in the area of sections 1–3.

Thickening in section 1–3 is formed in conditions of increasing reduction. This forms in this zone a forward zone. The forces and torques are at the level of the values of previous data presented in Fig. 5. The force and strain patterns are somewhat repetitive, although there are differences. Thin-walled part of the profile, as before, is rolled in conditions of decreasing reduction of tail part of the blade (the second thickening) and is formed in conditions of decreasing reduction. The maximum value of force in the area of sections 3, 4 represents the interface of metal flow in the longitudinal direction, defining the contours of lag and forward. As at rolling of sections presented in Figs. 4 and 5, there is a dip in the rolling force diagram in the transition zone from the tail part to the thin part of the airfoil (sections 6, 7, 8). This

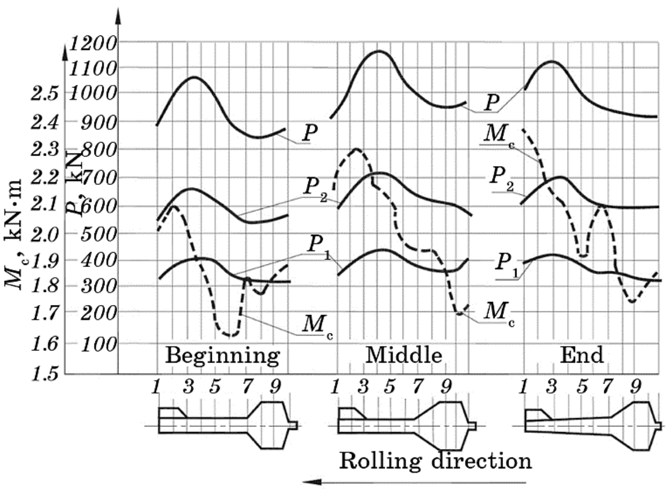

Fig. 6. Distribution of rolling force (P) and strain moment (M) along the length of one period of blades blanks of X stage of AI-20 compressor from steel 14X17H2-Ш.

phenomenon was explained by shear strains in this part of the profile, due to the multidirectional flow of metal in the longitudinal direction. This zone is characterized by a backward contour, *i.e.*, the flow of metal is opposite to the rolling direction. Therefore, in the contact layers, due to shear, additional tensile stresses may occur, reducing the rolling forces. The rolling moment in forward zone decreases its value, except for the end part of the strip.

Forces and torque reach their maximum values at the end of the strip, where the determining parameter is the temperature of the rolling end.

Presented analysis shows that during the rolling process of one period with the increase and decrease of reduction for different blade billet designs the distribution of contact normal pressures along the length of the strain zone at each point of time changes, which affects the force and torque. Experimental data show that the distribution of contact pressures during die rolling is determined by reduction, contact friction, through forward motion, as well as factors related to the non-uniformity of plastic strain along the length and height of the strip. The effect of shear strain shall be used when designing the technology and shape of workpieces for compressor blades.

4. CONCLUSION

In conclusion, it should be noted that the production of ‘thin-walled’ rolled products is always accompanied by a deterioration of the thermo-mechanical parameters of the process, which reduces the efficiency and the possibility of their production. The use of effects associated with non-uniformity of plastic strain makes it possible to compensate for the loss of manufacturability of 'thin-walled' profiles, to ensure reliable production with the fulfilment of specified profile dimensions, especially in the thickness of the rolled section. When rolling thin-walled die-rolled sections, it is a factor of influence on the shape change by intensive shear strain, by rolling a thin part of the profile under conditions of decreasing reduction.

REFERENCES

1. A. A. Nester, O. S. Drobot, and O. O. Nikitin, *Metallofiz. Noveishie Tekhnol.*, **44**, No. 4: 471 (2022) (in Ukrainian).
2. I. Volokitina, A. Kolesnikov, R. Fediuk, S. Klyuev, L. Sabitov, A. Volokitin, T. Zhuniskaliyev, B. Kelamanov, D. Yessengaliev, A. Yerzhanov, and O. Kolesnikova, *Materials*, **15**: 2584 (2022).
3. A. I. Denissova, A. V. Volokitin, and I. E. Volokitina, *Progress in Physics of Metals*, **23**, Iss. 2: 268 (2022).
4. R. Priestner, *Rev. Met. Paris*, **72**, No. 4: 285 (1975).
5. O. I. Gorbatov, Yu. N. Gornostyrev, P. A. Korzhavyi, and A. V. Ruban, *Fiz. Met. Metalloved.*, **117**: 1293 (2016).
6. C. Tung and P.-L. Tso, *Rotor World Academy of Science, Engineering and Technology*, **76**: 172 (2011).
7. N. V. Ruzanov, M. A. Bolotov, V. A. Pechenin, N. D. Pronichev, and E. R. Stepanova, *Proc. Eng.*, **176**: 529 (2017).
8. N. V. Ruzanov, M. A. Bolotov, V. A. Pechenin, and E. R. Matek, *Key Eng. Mater.*, **769**: 242 (2018).
9. V. V. Chigirinsky, Y. S. Kresanov, A. Y. Kachan, A. V. Boguslaev, G. I. Legotkin, A. G. Slepynin, T. G. Shevchenko, and N. H. Koretsky, *Proizvodstvo Tonkostennogo Prokata Spetsial'nogo Naznacheniya* [Production of Thin-Walled Rolled Products for Special Purposes] (Zaporizhzhya: Accent IT–VALPIS: 2014) (in Russian).
10. P. S. Prevéy, D. J. Hornbach, and J. T. Cammett, *6th Joint FAA/DoD/NASA Aging Aircraft Conference (Sept. 16–19, 2002)*, p. 9.
11. Yu. Ya. Meshkov and G. P. Zimina, *Metallofiz. Noveishie Tekhnol.*, **44**, No. 6: 807 (2022) (in Ukrainian).
12. F. Maturana and D. H. Norrie, *J. Intelligent Manufacturing*, **7**: 257 (1996).
13. G. Pijier, *J. Appl. Phys.*, **7**: 3706 (1980).
14. T. L. Subramanian, T. Altan, and F. W. Bougler, *CIRP Annals*, **1**: 123 (1978).
15. K. Chan, G. Mullineux, and W. Knight, *Metallurgy*, **1**: 24, (1980).
16. H. Kudo and S. Matsubara, *CIRP Annals*, **23**: 219 (1974).
17. M. O. Kurin, O. O. Horbachov, A. V. Onopchenko, and T. V. Loza, *Metallofiz. Noveishie Tekhnol.*, **44**, No. 6: 785 (2022).
18. V. Chigirinsky, A. Naizabekov, and S. Lezhnev, *J. Chemical Technology and Metallurgy*, **56**, 4: 867 (2021).
19. V. Chigirinsky and O. Naumenko, *Eastern-European J. Enterprise Technolo-*

gies, **5**: 56 (2020).
20. V. A. Boguslaev, A. Y. Kachan, V. F. Mozgovoy, and E. Y. Korenevsky, *Proizvodstvo Tonkostennogo Prokata Spetsial'nogo Naznacheniya* [Production of Thin-Walled Rolled Products for Special Purposes] (Zaporizhzhya: Publishing House of JSC 'Motor Sich': 2000) (in Russian).