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Study of Kinematic and Deformation Parameters of Rolling of Compressor Blade Workpieces

V. V. Chigirinsky, Yu. S. Kresanov*, and I. Ye. Volokitina

Rudny Industrial Institute,
38, 50 Let Oktyabrya Str.,
KZ-111500 Rudny, Kazakhstan
** 'Motor Sich' JSC,*
15 Motorobudivnykiv Ave.,
UA-69068 Zaporizhzhia, Ukraine

The article presents experimental research of kinematic and deformation parameters of die rolling of compressor-blades' workpieces made of titanium alloy BT–8, using a section mill 330 of 'Motor Sich' JSC. The experimental results confirm that the strain unevenness is associated with intense shear, which is determinant in the formation of individual elements of the profile. Metal moves from areas of high reduction to areas of lower reduction in both the transverse direction and the longitudinal one. The use of uneven plastic deformation to control the process of forming the rolled products of different configurations and purposes is of interest.

Key words: blade, aircraft engine, power parameters, die rolling, workpiece.

У статті наведено результати експериментальних досліджень кінематичних і деформаційних параметрів періодичного вальцювання заготовок компресорних лопаток з титанового стопу ВТ–8 в умовах сортового стану 330 АТ «Мотор Січ». Результати експерименту підтвердили, що нерівномірність деформації пов'язана з інтенсивними зсувами, які є визначальними під час формування окремих елементів профілю. Метал переміщається з областей з більшим обтисненням в області з меншим, як у поперечному, так і в поздовжньому напрямках. Становить інтерес використання нерівномірности пластичної деформації для управління процесом формування прокату різної конфіґурації та призначення.

Corresponding author: Iryna Yevgenivna Volokitina
E-mail: i.volokitina@alservice.kz

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

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1. INTRODUCTION

Currently, the share of imports in the cost of domestic aircraft engine construction is quite high. In this regard, the development of import substitution and export of domestic blades becomes especially relevant. The most important condition determining the expediency of import substitution is the ability to provide required innovative level of domestic production of aircraft engines and recognition of their competitiveness in foreign markets [1–3]. Modernization of existing production facilities, first of all, of the most used parts that make up modern aircraft engines, makes it possible to ensure the competitiveness of manufactured blades.

Blade production occupies the main place in the structure of gas turbine engine production. This is caused by the greatest applicability (large number of parts) of these parts in the composition of engines (Fig. 1); the most significant weight in the labour costs of production; the shortest life compared with the life of other types of parts [4–6].

New generation engines compared to the previous generation engines should have 1.5–2 times lower specific weight and volume; 15–30% lower fuel consumption. In this case, the level of operational characteristics should be increased, namely: increased reliability by at least 60–80%; increased service life; reduced labour intensity of pro-

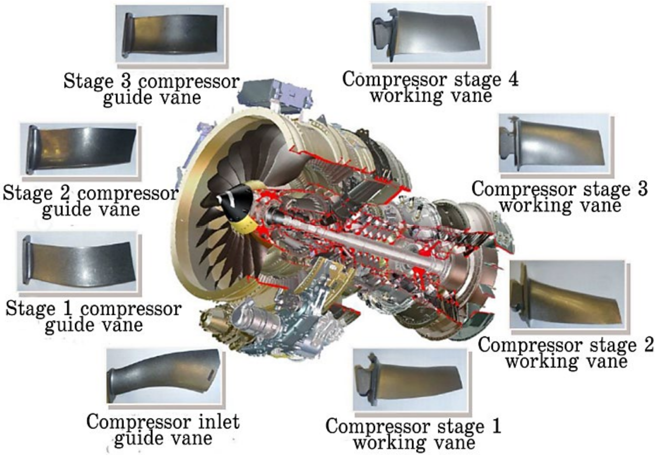


Fig. 1. Sam146 engine compressor blades.

duction by at least 2 times; reduced cost of life cycle by at least 1.5 times.

Ensuring fundamentally new type of production requires solving a large number of scientific and technical problems, including the development of technological support for the production of compressor stator and rotor blades in accordance with the first accuracy class according to OST 1.02571–86.

The design of compressor blades is constantly becoming more complex, their load-bearing capacity is increasing, and more difficult-to-machine materials are used for their production. The complexity of geometric shape, the use of hard-to-deform and hard-to-machine materials results in a low metal utilization factor and high labour intensity of manufacturing.

Conventional manufacturing processes of precision blades workpieces in most enterprises of the industry, both in Ukraine and abroad, include several straining operations (pre-forming, stamping, calibration, burr cutting) with multiple heating of workpieces, which leads to the formation of defective layer on the workpieces and large metal losses to burr and scale.

Application of more advanced technological processes, such as isothermal stamping, superplastic deformation stamping, high-speed stamping allows to increase accuracy of stamping and metal utilization factor [7–11]. Despite this, the main disadvantage of these methods remains high labour intensity and high cost of production of compressor blades workpieces.

Issues of workpiece production, stamping processes in general and aircraft engineering, properties and features of titanium alloys have been considered in the works of many scientists: A. M. Sulima [12], V. I. Omelchenko [13], V. V. Krymov [14], V. A. Likhovitser [15], P. D. Zhemanyuk and V. F. Mozgovoy [16], J. Fix [17], D. H. Norrie [18], J. Haton [19], G. Pijier [20], *etc*.

Compressor blades manufacturing problems are not only related to the complexity of the forging shape, but also to the high accuracy requirements for them. The ratio of the cross-sectional area of the shank to the cross-sectional area of the flowing part of the compressor blades of the last stages is constantly growing. Therefore, their production requires an increase in the number of stamping transitions, which results in an increase in the amount of metal that goes into the scrap, increases the rate of material consumption.

In this regard, there is a need to improve workpiece production through the development and implementation of deformation processes that ensure a minimum number of transitions.

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 (Zaporizhzhia) [21].

Compressor blade workpieces, like wheel rims, are a ‘thin-walled’ special profile, which is quite difficult to roll at section mill 330. Rolling force increases sharply due to rapid cooling of the rolled product in the thin feather area, which leads to large elastic deformations of the working stand. It is not always possible to make a profile with a minimum thickness because of this limitation.

The task is relevant if the technological solution to obtain a thin profile of high quality is defined.

Because of the tool action, the deformed metal can undergo intense shear deformation, which forms entire profile elements. The study of die rolling with increasing and decreasing reduction revealed [22] that the process is accompanied by unevenness of deformation along the thickness, which increases with increasing reduction. Longitudinal uneven metal flow in the squeeze area is obviously determinative. Therefore, the shear deformations in this zone of the profile are determinative.

Therefore, it is necessary to create conditions that make it possible to roll steadily a thin part of the profile.

In this regard, the work objective is to improve the manufacturing accuracy of compressor blades by studying the kinematic and deformation parameters of die rolling of workpieces.

2. EXPERIMENTAL

To identify the effects of shape change, elimination of defects in rolling production it is necessary to know the general laws of metal flow when rolling the compressor blade workpieces on the surface and in the volume. For this purpose, an experiment [22] was planned and carried out under conditions of industrial mill 330 of ‘Motor Sich’ JSC. 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.

First, the metal flow was studied on the rolling surface using a coordinate grid during round profile plowing. Second, the surface in longitudinal and transverse sections and in the volume of the deformation zone using ‘witnesses’ for the die profile of the blade workpiece was studied.

Round blanks were rolled into flat blanks, and then flat ones were rolled into compressor blade workpieces. The titanium alloy BT–8 was used. A grid with square cells of 4×4 mm with a depth of 0.2 mm and an accuracy of 0.02 mm was applied to the surface of flat samples of 9 mm height, 21 mm width and 120 mm length. Optimal cell sizes were determined after rolling samples with cells of 2×2 mm and 6×6 mm, *etc*. A grid with a cell size of 2.9×2.9 mm was applied to round samples with a diameter of 18.5 mm and a length of 80 mm. Cell dimensions before and after rolling were determined on a universal instrumental microscope UIM-21 with an accuracy of ±0.005 mm.

The rolls were wiped with fine sandpaper and washed with acetone before rolling to conduct tests under the same conditions. Lubrication of rolls and samples was carried out with boron nitride powder.

To determine the nature of volumetric flow of metal in the deformation zone, M5 threads with a pitch of 0.8 mm were cut in flat workpieces. The screws and workpiece material were made of the same alloy BT–8 and were screwed in vertical and horizontal directions. Samples before rolling were heated in an electric furnace to a temperature of 920°C for 18–20 min and rolled with decreasing reduction on the blade airfoil in rolls with a diameter of the initial circle of 340 mm.

3. RESULTS AND DISCUSSION

Figure 2 shows the strain field in the corresponding directions when rolling round workpieces. The strain variation in the longitudinal direction (X-axis) is insignificant. Strain in the transverse direction (Y-axis) changes sharply from the middle to edges of the sample.

This strain indicates an uneven distribution of widening across the width of the strip with maximum concentration in the lateral zones. There are 2 hypotheses of widening distribution: uniform and non-uniform along the strip width [23]. In this case, in the surface layers, this distribution appears to be uneven.

Figure 3 shows the distribution of displacement and strain zones in longitudinal and transverse directions during die rolling of blades. Straining of surface metal layers increases from thin to thick, reaching a maximum at the transition from the airfoil with greater height to

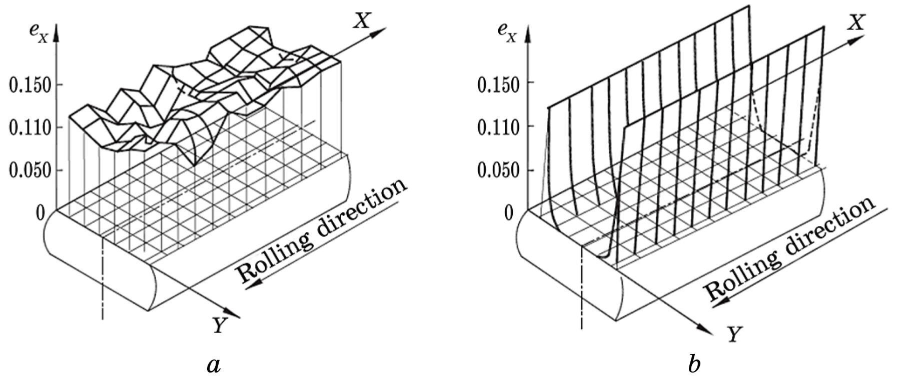
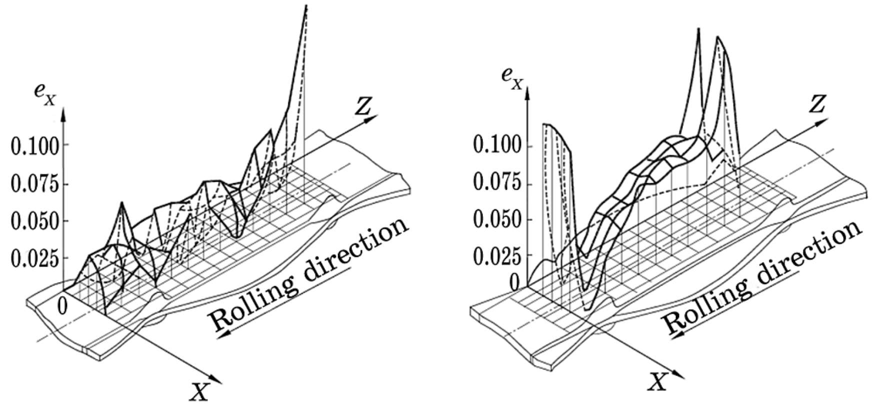


Fig. 2. Strain zone during rolling of round samples: in longitudinal direction (*a*); in transverse direction (*b*).



a *b*

Fig. 3. Strain zone during rolling of compressor blade workpieces: in transverse direction (*a*); in longitudinal direction (*b*).

the shank. The values of relative strain change insignificantly along the width and are distributed approximately evenly. If to compare the distribution of relative reduction during rolling along the sections of the profile with the distribution of longitudinal strains (Fig. 3), their nature is mutually opposite. In the area of maximum airfoil reductions, linear longitudinal strains on its surface are minimal, and vice versa. That is, relative vertical reduction does not correspond to the longitudinal strain on the surface. Moreover, the longitudinal metal flow on the surface in the area of maximum reduction tends to zero. To explain this phenomenon, an additional study of the metal flow not only on the surface, but also in the volume of the rolled strip was carried out.

Kinematic parameters of die rolling of compressor blades workpieces of variable cross-section with increasing reduction (Fig. 4) in enclosed box gauges with gates were investigated. Gauge lateral walls increase pulling forces and the angle of neutral section along the bottom of the gauge.

In longitudinal die rolling, the advance determines the geometric dimensions of strips. Variable-section strips are rolled at small widths with high reductions, which may be up to 70% or more. Let us consider the definition of immediate advance taking into account the strip widening in strain zone. Figure 5 shows experimental and calculated data of strip advance [22] during rolling with increasing and decreasing reduction in comparison, where solid lines are experimental data, and dashed lines are calculated data. Under the experimental conditions, the formulas give good correlation except for the section of minimum thickness (1.85–1.90 mm).

Results obtained from the study of kinematic parameters of die roll-

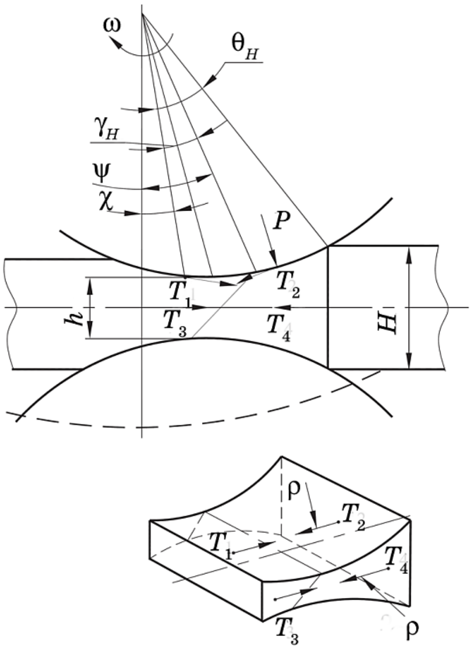


Fig. 4. Force action scheme at the metal contact with rolls in closed gauges with increasing reduction.

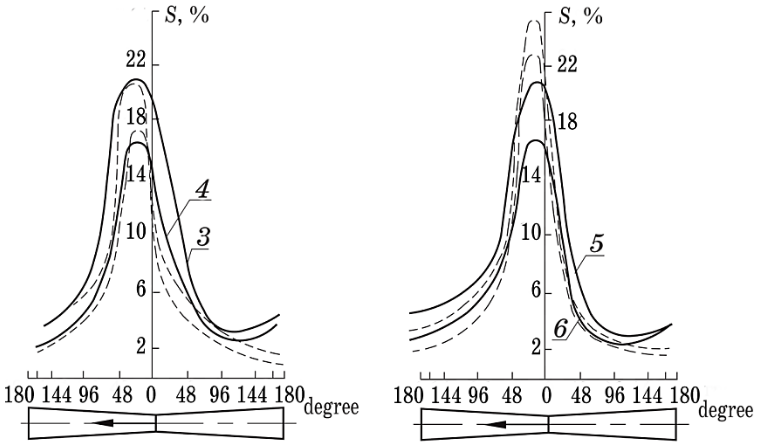


Fig. 5. Experimental and calculated advance values.

ing process have shown that the longitudinal flow of metal occurs according to more complex schemes than in the simple case of rolling.

There are peculiarities of the shape change with increasing and decreasing reduction in strain zone. Different advance along the length leads to different 'printability' of the roll on the strip. There is a need to link the parameters of metal forming with factors affecting the advance, the delay of the strip under increasing and decreasing reduction.

The theoretical studies obtained clearly show that the kinematics of strain zone is different for increasing and decreasing reduction. A rather fundamental question is where to place the rolling of the thin part of the profile—in decreasing or increasing reduction zone. This depends on the rolling direction and can be decisive when mastering and producing these sections. The impact of the tool on the metal along the length of strain zone is different. Decreasing reduction zone is mainly characterized by 'sloping' movement of metal; an advance zone is steadily formed in increasing reduction zone.

In decreasing reduction zone, mainly only 2 forces act on strain zone—pushing force of normal pressure and retracting force of friction of delayed zone. Tensile longitudinal stresses appear in the zone under these forces. In the case of limiting gripping or slipping, the action of these stresses becomes determinative, the pressure decreases, and the peak of diagram of contact normal stress is cut off [23]. If there is an advance zone in the strain zone, which is the case with increasing reduction, the length of delayed zone decreases, the value of pulling friction force and the value of longitudinal tensile stresses also decrease. In increasing reduction zone, the impact of pushing normal force on metal flow weakens, which also contributes to the reduction of tensile stress. Thus, rolling a thin section when increasing or decreasing the reduction will occur under different strain and force conditions. In addition, knowing the manufacturing process of special profiles, such as blade workpieces with a large volume of tail part, is also necessary in terms of eliminating certain types of defects in rolling production, such as the formation of laps, cracks and 'shackles'.

Different options of metal flow have been studied. In this case, the study of thin section rolling process in the zone of decreasing reduction along the length of airfoil is presented. Longitudinal tensile stresses in this zone will reduce the rolling force, elastic deformation of the working stand, improve the conditions for rolling a thin section and, consequently, obtain the minimum thickness of the rolled section [24].

Figure 6 shows metal flow from the thin part of the profile to the tail part.

The blade airfoil is rolled from larger diameter to smaller one, *i.e.*, in the area of decreasing reduction. In this zone, mainly the delay contour is formed, *i.e.*, metal backflow zone. For the inner layers, the metal backflow is understandable because there is a movement from higher-pressure areas to lower pressure areas. When shaping the blade tail part, the metal enters gauge cavity in the opposite direction to the roll-

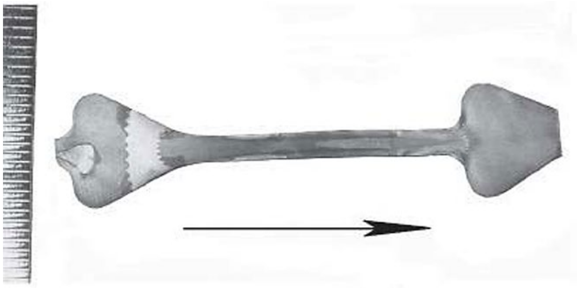


Fig. 6. Longitudinal strain distribution, when rolling compressor blades (vertical screw position).

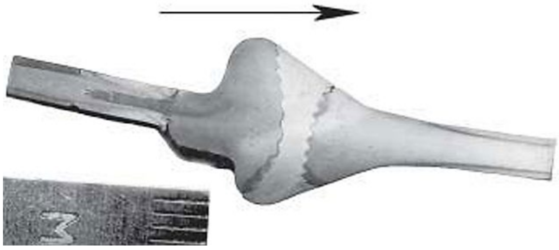


Fig. 7. Longitudinal strain distribution during rolling compressor blades (vertical screw position).

ing direction (Fig. 6). In this case, central layers move in longitudinal direction more intensively than surface layers, forming left convexity.

The metal flow in tail part of the profile is of interest. There is a zone of sharp reduction decrease and a zone of reduction increase in a small section of the strain zone, with insignificant height strain. In decreasing reduction zone, the delay contour is formed, and in increasing reduction zone the advance contour is formed (Fig. 7).

Metal of profile tail part, being exposed to the influence of oppositely flowing metal flows from the side of the specified contours, is in a state of longitudinal reduction. This is clearly seen in Fig. 7.

The increase in ‘witness’ length at the contact with the tool is explained by the flow of metal up or down, when filling the empty space of gauge and relatively small reduction in height.

Figure 8 shows the metal flow in the transition from the tail part of the profile to the airfoil side of delay contour. The peculiarity of metal flow in this area is a longitudinal retraction of surface layers of the shank into the airfoil area.

Figure 8 shows that there is an intensive non-uniform plastic deformation at a small height of airfoil part of the profile. Metal flows on the contact and in the middle part in mutually opposite directions, cre-

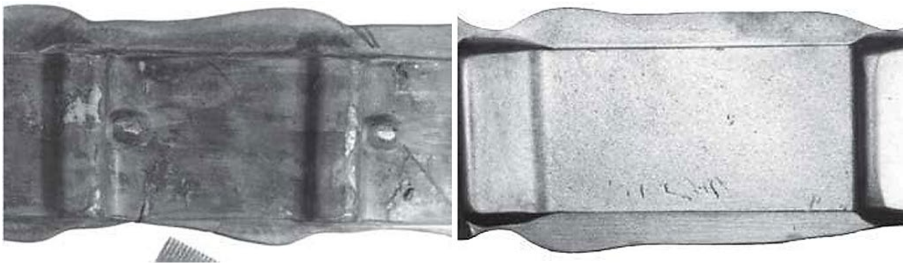
Fig. 8. Tail-to-airfoil transition section.

ating intense shear, when the surface layers of metal penetrate under the roll for a considerable distance deep into the airfoil. This provides an intense flow of surface layers in the rolling direction. Retraction of surface metal layers in the area of airfoil zone is due to the action of significant magnitude of contact frictional forces, determined by the flow of metal in delay zone. Acad. A. I. Tselikov in his paper [23] has the same opinion. Longitudinal metal flow in the rolling direction of the surface layers creates preconditions for advance contour formation in the airfoil part, and further, in the area of maximum reduction, it forms the advance contour.

Intense shear deformation in this zone explains the large longitudinal surface deformations shown in Fig. 3. Indeed, the roll as if 'licks off' the surface layers of metal in a zone of significant height difference of the profile in tail part, contributing to the longitudinal metal flow in the rolling direction.

In the pinch zone (of minimum profile thickness), the deformation of relative reduction is maximal, and on the surface of rolling the longitudinal deformation is minimal (Fig. 3). It was found that the metal flows from areas of higher pressure or reduction to areas of lower pressure or reduction. The pinch is a kind of interface of metal flow in the longitudinal direction, forming the contours of delay and advance, in the zone of which longitudinal movements are absent or insignificant. The longitudinal metal flow in decreasing reduction zone in the opposite direction to the rolling for the centre layers in height forms a left-hand convexity at the entrance to the gauge. Thus, these experimental studies show the complex kinematics of metal flow during die rolling, which is accompanied by a mutually opposing metal flow along the height of the airfoil, with intense shear deformation within a small height of the profile thin part.

The occurrence of shear deformations in this part of the profile should be linked with experimental data on measuring the forces and



a *b*

Fig. 9. Cracks on the surface of thin-walled part of the profile: steel 14X17H2 (*a*), titanium alloy BT–8 (*b*).

torques of rolling along the length of a die roll. It is known that the occurrence of intense shear deformation changes the rolling force in magnitude, but does not change the energy parameters of the process.

When rolling the blades workpieces with decreasing reduction, die cracks appear on the surface of the thin part of the profile at the reduction of more than 70%. This indicates the longitudinal tensile stresses in the strain zone (Fig. 9).

This phenomenon was explained above. First of all, it is related to the formation of delay contour in the decreasing reduction zone. With a small advance zone in the strain zone or its absence, longitudinal tensile stresses arise in the metal in the longitudinal direction, reducing the contact normal stresses.

In ultimate case, a gap is formed in the force diagram along the length of the roll, and the diagram of contact normal stresses is sheared. It should be added that reducing the friction ratio during rolling (the use of grease) leads to the destruction of the metal as it leaves the strain zone. This is well explained by the influence of friction conditions on the kinematics of the strain zone. As the friction ratio decreases, according to the Ekelund–Pavlov formula, the neutral angle decreases, hence the advance zone. Turning to the ultimate case of rolling, when there is no advance zone, we have the maximum value of tensile stress resulting from the pulling forces of friction and pushing forces of normal pressure. Tensile stresses reach extreme values at small profile thicknesses, leading to the destruction of the metal (Fig. 10). This example indicates: first, metal backflow, *i.e.*, delay, is observed in the reduction zone; second, tensile stresses are in this zone, which is not only a negative factor in rolling, but also positive, because it reduces the force of forming. This defect can be eliminated by rolling the blades workpieces in two ways: rolling with increasing reduction in the thin-walled part of the profile, changing the rolling direction and reducing the radius of transition from airfoil to shank from 5 mm to 20 mm. In the first case, there is an advance zone, which

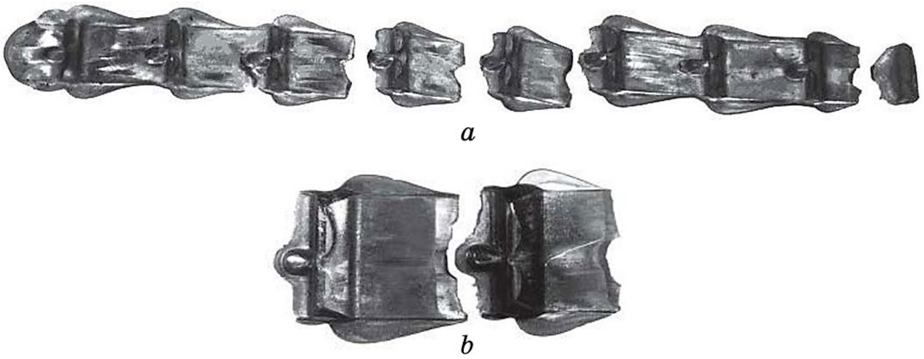


Fig. 10. Strip rupture during die rolling with effective (plentiful) lubrication of blades workpieces of 4 stage of AI20 engine compressor made of 14X17H2SH steel: strip (*a*), part (*b*).

reduces the forces that create tensile stresses in the strip. In the second case, the flow of surface layers of metal is broken that reduces uneven plastic deformation decreasing the value of tensile additional stresses in the near-contact layer. The latter case indirectly confirms the influence of uneven deformation on the stress state of the strip in the transition area from tail part to thin-walled.

Figure 11 shows a cross section of thin section of the profile. It shows the airfoil deformation in the transverse direction. The maximum height deformation is observed in the central part along the section height. 'Witness' has maximum thinning in the vertical direction. In the transverse direction of airfoil, the screw has lengthened in this area as evidenced by the increase in pitch of its thread. In the lateral areas of the profile at the junction with the burr, the screw metal moves to the surface layers, and it goes to its surface in the burr itself. More detailed analysis of metal-flow kinematics shows that layers central in width and surface in height are reduced insignificantly that is obviously due to a sticking zone on the contact (of the greatest thickness of the dark layer).

Fig. 11. Cross-section strain distribution, when rolling compressor blades (horizontal screw position).

The midsection height is reduced as much as possible, where the influence of contact friction on metal flow is weakened. Transverse movement of material particles in this zone is also maximum that corresponds to vertical reduction. Vertical deformation increases in the lateral areas of the cross section, where the influence of the sticking zone (contact friction) is weakened. This is confirmed by a dark layer thickness decrease. In this case, the reduction of the peripheral contact area occurs not only from above the tool, but also from below the metal layers coming out from under the weakly deformed contact central layers. The latter fact to some extent explains the formation of 'transverse crack' during sinking strain and rolling. The lower reduction of peripheral contact areas is to some extent unexpected.

The spreading deformation volume of 'witness' metal in the lateral zone of airfoil cross section simultaneously in two directions (longitudinal and vertical up or down) shows the complex kinematics of metal flow, which is difficult to explain by the linear and shear components of the strain tensor. The metal particles still perform a rotational motion in these areas. This is confirmed by the transition of lateral surfaces of strained metal to the contact surface.

The formation of rolling production defects for this type of product can be explained based on experimental data on metal flow kinematics during rolling of compressor blade workpieces. Figure 12 shows a schematic strain zone, when rolling a compressor blade workpiece with a large volume of the tail part. When turning an angle (Fig. 12), the gauge with a variable radius moves along the rolling and forms different contours—delay and advance.

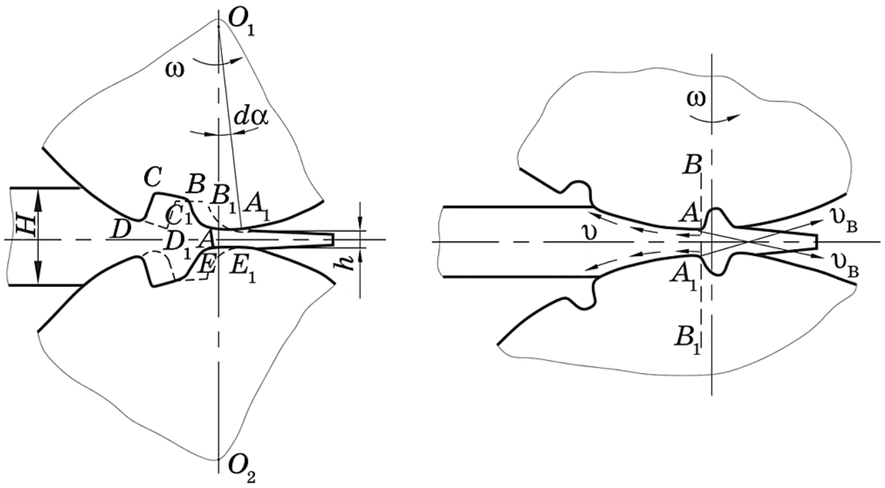


Fig. 12. Schematic strain zone, when rolling a compressor blade workpiece with a large volume of the tail part.

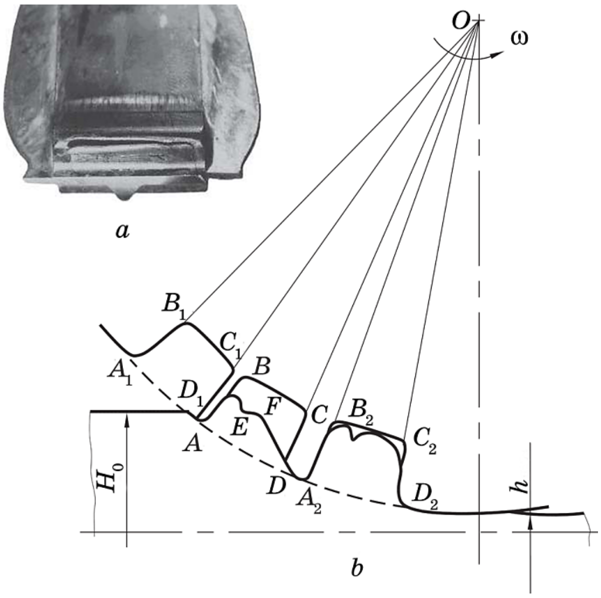


Fig. 13. ‘Forging fold’ formation.

After the strip is touched by a point of rolls D (position D_1), the delay come out from under the edge DC, *i.e.*, section of the strip with metal backflow (Fig. 13, *b*). Then, as the AB edge starts to be introduced (increase in reduction), an overlap is formed. There is a tendency to form an advance contour in the zone of maximum reduction. The metal is strained in the longitudinal direction as it rolls, but the metal forming the delay contour (Fig. 12) resists it. If this resistance was not in place, then, the advance contour appeared from under the AB edge, *i.e.*, the section of the strip in which the metal flow would coincide with the rolling direction. In this case, of course, we cannot talk about any overlap.

During the rolling process, the surface of BC roll, located on gauge bottom, begins to interfere with metal flow, which is associated with the delay contour. The resulting overlap begins to deform, forming a fold—‘forging fold’ (see Fig. 13, *a*).

Cracks may occur in the transition area between the tail part and the airfoil of the workpiece because of the complex kinematics of metal flow. There can be even a separation of tail part from the rolled metal. This is explained by the occurrence of intense shear deformations in the zone and by the fact that the rear part of the gauge transports the tail at maximum speed along the rolling path. Metal flows behind the shank in the opposite direction, defining the delay contour (Figs. 6–7). This position is confirmed by the results of the research paper [22].

4. CONCLUSION

In conclusion, it should be noted that the plastic deformation of the blade workpiece is characterized by the complexity of the process and a large unevenness of the shape change along the length and height of the profile. There are intense shear deformations in the transition zone from tail part to airfoil part, determined by the opposite metal flow in the thin part of the strip. Indirect data from such a study show that tensile stresses are present on the contact surfaces of this zone. The formation of shears in the transition zone is one of the features of plastic deformation when rolling a profile with variable thickness. Another feature is the rolling of the thin part of the profile in decreasing reduction zone. This causes tensile longitudinal stresses in the strip, which reduces the rolling force, the elastic deformation of working stand, allows obtaining a minimum rolling thickness of hard-to-deform alloys and steels.

REFERENCES

1. Yu. Ya. Meshkov and G. P. Zimina, *Metallofiz. Noveishie Tekhnol.*, **44**, No. 6: 807 (2022) (in Ukrainian).
2. A. I. Denissova, A. V. Volokitin, and I. Ye. Volokitina, *Progress in Physics of Metals*, **23**, No. 2: 268 (2022).
3. 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).
4. V. V. Chigirinsky, Yu. 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] (Zaporizhzhia: Accent IT–VALPIS: 2014) (in Russian).
5. M. O. Kurin, O. O. Horbachov, A. V. Onopchenko, and T. V. Loza, *Metallofiz. Noveishie Tekhnol.*, **44**, No. 6: 785 (2022).
6. P. S. Prevéy, D. J. Hornbach, and J. T. Cammett, *Ravindranath 6th Joint FAA/DoD/NASA Aging Aircraft Conference* (2002), p. 9.
7. V. A. Korneev and M. N. Tutunin, *Sposob Izgotovleniya Lopatok iz Dvukhfaznykh Titanovykh Splavov* [Method of Manufacturing Blades from Two-Phase Titanium Alloys]: Patent 660770 USSR. B21K 3/04 (Otkrytiya i Izobreteniya, 17) (1977) (in Russian).
8. V. V. Andreev, V. B. Bystrov, and R. A. Kazakov, *Sposob Izgotovleniya Shtampovok Lopatok iz Dvukhfaznogo Titanovogo Splava* [Method of Two-Phase Titanium Alloy Blade Forgings Production]: Patent 2525961RU. B21K3/04 (Otkrytiya i Izobreteniya, 17) (2013) (in Russian).
9. M. Bénion, B. Bouillot, L. Valéry, C. Kounier, M. Lepti, and J.-C. Plazane, *Sposob Izgotovleniya Detaley Tochnoy Ob'emnoy Shtampovkoy* [Method of Manufacturing Parts by Precision Volume Stamping]: Patent 2355503RU. B21J 5/02 (Otkrytiya i Izobreteniya, 32) (2004) (in Russian).

10. V. V. Chigirinsky, G. I. Legotkin, A. G. Slepynin, V. I. Kozlov, and V. V. Dragobetsky, *Metallurgical and Mining Industry*, **11**: 222 (2015).
11. A. A. Nester, O. S. Drobot, and O. O. Nikitin, *Metallofiz. Noveishie Tekhnol.*, 44, No. 4: 471 (2022) (in Ukrainian).
12. A. M. Sulima, A. A. Noskov, and G. Z. Serebrennikov, *Osnovy Tekhnologii Proizvodstva Gazoturbinnykh Dvigateley* [Fundamentals of Gas Turbine Engines Production Technology] (Moskva: Mechanical Engineering: 1996) (in Russian).
13. V. I. Omelchenko and Yu. S. Kresanov, *Sposob Izgotovleniya Soplovykh i Napravlyayushchikh Lopatok Gazoturbinnykh Dvigateley* [Method of Fabrication of Nozzle and Guide Vanes for Gas-Turbine Engines]: Certificate of Inventory788522USSR. B21K 3/04 (Otkrytiya i Izobreteniya, 46) (1980) (in Russian).
14. B. V. Krymov, Yu. S. Eliseev, and K. I. Zudin, *Proizvodstvo Lopatok Gazoturbinnykh Dvigateley* [Production of Gas Turbine Engine Blades] (Moscow: Mechanical Engineering: 2002) (in Russian).
15. B. A. Likhovitser, V. F. Sorokin, and E. R. Lipsky, *Avtomatizirovannoye Proyektirovanie i Izgotovlenie Osnastki so Slozhnofasonnymi Poverkhnostyami v OAO 'Motor Sich'* [Automated Design and Manufacturing of Tooling with Complex Shaped Surfaces at OJSC 'Motor Sich'] (Forging and Stamping $_{\text{P}}$production: 2002) (in Russian).
16. V. A. Boguslaev, P. D. Zhemanyuk, and V. F. Mozgovoy, *Avtomatizatsiya Tekhnicheskoy Podgotovki Proizvodstva v OAO 'Motor Sich'* [Automation of Technical Preparation of Production at OJSC 'Motor Sich'] (Technological Systems: 2003) (in Russian).
17. J. Fix, *Dymat'88* (1998), p. 18.
18. F. Maturana and D. H. Norrie, *Journal of Intelligent Manufacturing*, **7**: 257 (1996).
19. J. Haton, *Natur Wissenchaften*, 487 (1970).
20. G. Pijier, *J. Appl. Phys*, **7**: 3706 (1980).
21. V. A. Boguslaev, A. Y. Kachan, V. F. Mozgovoy, and E. Y. Korenevsky, *Proizvodstvo Tonkostennogo Prokata Spetsial'nogo Naznacheniya* [Technology of Aircraft Engines Production] (Zaporizhzhia: Publishing House of JSC 'Motor Sich': 2000) (in Russian).
22. Y. S. Kresanov, A. V. Boguslaev, and A. Y. Kachan, *Periodicheskaya Prokatka Zagotovok Lopatok Kompressora Gazoturbinnykh Dvigateley s Aehrodinamicheskim Profilem* [Periodical Rolling of Gas Turbine Engine Compressor Blades Blanks with Aerodynamic Profile] (Engine Construction Bulletin: 2006) (in Russian).
23. A. I. Tselikov, *Teoriya Raschyota Usiliy v Prokatnykh Stanakh* [Theory of Calculation of Efforts in Rolling Mills] (Moskva: Metallurgizdat: 1962) (in Russian).
24. V. Chigirinsky and O. Naumenko, *Eastern-European Journal of Enterprise Technologies*, **5**: 56 (2020).