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INVESTIGATION OF FORWARD SLIP DURING HOT ROLLING OF THE AK6 ALUMINUM ALLOY

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The article presents the results of a comprehensive study of forward slip during hot rolling of the wrought aluminum alloy AK6. Forward slip, defined as the difference between the circumferential speed of the rolls and the actual exit velocity of the metal from the deformation zone, is a key kinematic parameter that determines the accuracy of calculating the elongation zone length and ensures proper synchronization of successive passes in the technological process. Even a minor error in estimating this value may lead to the accumulation of geometric deviations, malfunction of the roll grooves, and defects at subsequent processing stages.

The aim of the study is to determine the regularities of forward slip variation depending on the rolling temperature conditions, degree of deformation, billet geometry, and roll-heating temperature. A series of experiments was carried out using AK6 alloy billets with diameters of 14–25 mm under reductions of 30, 40, and 50 % in smooth rolls with controlled temperature. The billets were heated to 450 °C, while the roll temperature varied from 20 to 450 °C. During rolling, forward slip was recorded and compared with the well-known analytical models of Pavlov, Fink, Ekelund, and Dresden–Golovin.

The results show that forward slip increases with higher reductions due to greater elongation and redistribution of velocities in the near-surface layers. Increasing both billet and roll temperatures reduces the friction coefficient, enhances metal plasticity, and intensifies dynamic recovery and recrystallization processes, which leads to increased forward slip. It was established that within the temperature range of 200–350 °C, at constant reduction, the influence of roll heating is minimal and forward slip changes only slightly. However, further heating to 450 °C results in a significant increase in the parameter – up to 47 %, depending on the deformation level.

The obtained dependencies make it possible to evaluate the influence of key technological parameters on the kinematic behavior of AK6 alloy and improve the accuracy of predicting geometric characteristics during hot rolling. The results can be applied to the optimization of reduction schedules, thermal preparation of billets and rolls, as well as to analytical and numerical deformation models for aluminum alloys.

Key words: *billet, deformation, elongation, plastic deformation, strain intensity, stress–strain state, plasticity, technological process, aluminum alloys.*

Eq. 5. Fig. 3. Ref. 11.

1. Problem formulation

Rolling is one of the most widely used metal forming processes, enabling the production of billets and profiles with the required geometric parameters and specified properties. One of the key aspects of controlling the process is the accurate determination of kinematic characteristics, among which forward slip–defined as the relative increase in the exit velocity of the metal from the deformation zone compared to the circumferential speed of the rolls–plays a particularly important role. Forward slip largely determines the length of the deformation zone, the accuracy of profile formation, and the alignment of passes between successive rolling stages.

In the rolling of aluminum alloys, particularly the highly deformable AK6 alloy, the value of forward slip is critically important because the deformation and kinematic properties of the material strongly depend on temperature. Unlike cold rolling, where structural changes are minimal and the dominant processes are work hardening and friction, hot deformation is characterized by complex thermoplastic interactions. Elevated temperatures intensify dynamic recovery and recrystallization, reduce the flow stress, promote redistribution of the stress–strain state, and alter the metal flow kinematics within the deformation zone. As a result, forward slip during hot rolling differs significantly from that observed under cold processing conditions.

During cold rolling, forward slip is generally lower and more stable due to the high friction coefficient,

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pronounced work hardening in the near-surface layers, and the absence of thermally activated recovery processes. In contrast, during hot rolling of Al–Mg–Si system alloys, including AK6, forward slip exhibits a complex dependence on billet heating temperature, roll temperature, reduction ratio, and the initial billet diameter and width. This necessitates dedicated studies for various thermomechanical regimes, as inaccuracies in determining forward slip can lead to substantial errors in estimating the deformation zone length, disruption of pass synchronization, and the appearance of defects.

In the current stage of development of hot-rolling technologies for aluminum alloys, an important task is the creation of more accurate models that account for the rheological behavior of the metal, the temperature-dependent variation of the friction coefficient, and the structural transformations occurring in the "metal–roll" contact zone. For AK6 alloy, widely used in the transportation, mechanical engineering, and aerospace sectors, the study of forward slip is particularly relevant, as this alloy is highly sensitive to deformation temperature and capable of significant elongation under hot working conditions.

Thus, investigating the regularities of forward slip formation during the hot rolling of AK6 aluminum alloy, as well as comparing its behavior to that under cold deformation, makes it possible not only to deepen the understanding of the physical mechanisms of metal flow kinematics but also to enhance the accuracy of technological calculations, optimize thermal regimes, and reduce geometrical deviations during shape formation. These considerations underpin the relevance of the present study.

2. Analysis of recent research and publications

The kinematics of rolling and the role of forward slip have been extensively studied in both classical and modern works. Analytical models proposed in [2–5] describe forward slip through the geometry of the deformation zone and friction conditions [3, 4]. These approaches provide a reliable basis for cold rolling; however, their applicability to hot deformation is limited because they do not fully account for temperature-dependent rheology and structural transformations.

Roberts and Hirsch emphasized that in hot rolling, metal flow is governed by complex thermomechanical interactions, including dynamic recovery and recrystallization, which significantly modify deformation kinematics [2]. Experimental investigations by Skriabin demonstrated that for aluminum alloys, forward slip depends nonlinearly on billet temperature, reduction, and geometry [1]. Industrial studies further showed that forward slip can serve as an indirect indicator of the friction coefficient, which decreases exponentially with temperature in the roll–metal contact zone [5].

Recent research integrates experimental observations with deformation mechanics and plasticity theory. These works revealed the influence of strain localization and plasticity redistribution on metal flow during rolling-based forming processes [6, 7]. Haydamak and co-authors highlighted the effect of thermal treatment and structural evolution on the stress–strain state and subsequent deformation behavior [8, 9].

Despite these advances, systematic data for high-plasticity Al–Mg–Si alloys, particularly AK6, remain scarce. Existing studies rarely consider the combined influence of billet temperature, roll heating, reduction, and billet geometry on forward slip. This gap limits the accuracy of current models for hot rolling of such alloys and substantiates the need for a dedicated experimental and analytical investigation.

3. The purpose of the article

The aim of this study is to conduct a comprehensive experimental and analytical investigation of the regularities of forward slip formation during the hot rolling of the wrought aluminum alloy AK6, to determine the influence of temperature–velocity and geometric process parameters on the magnitude of kinematic forward slip, and to identify the mechanisms of interaction between friction, plastic deformation, and structural transformations of the metal under hot deformation conditions.

4. Results and discussion

Forward slip is one of the key kinematic characteristics of the rolling process and defines the relationship between the circumferential speed of the rolls and the actual exit velocity of the metal from the deformation zone. Its occurrence is governed by a combination of several physical mechanisms that manifest during the hot deformation of the AK6 alloy.

The first factor is the variation in metal flow velocity from the neutral section toward the exit plane, where elemental metal volumes acquire additional acceleration due to strip thickness reduction and the redistribution of internal stresses. The second factor is the formation of near-surface zones of intensified deformation, which arise as a result of localized strengthening during hot rolling. These zones act similarly to an increase in the effective roll diameter, causing the deeper layers of the billet to move at a velocity exceeding the circumferential speed of the rolls. The third mechanism is the increase in the axial component of velocity in the metal exit region, particularly when lateral spread is minimal, while the circumferential roll speed remains constant.

Classically, forward slip is defined by the following expression:

$$s = \frac{v_{met} - v_{roll}}{v_{roll}} \quad (1)$$

where s is – the relative forward slip; v_{met} – is the exit velocity of the metal; v_{roll} – is the circumferential speed of the rolls [2].

In a number of analytical models (Pavlov, Fink, Ekelund, and Dresden–Golovin), forward slip is expressed through the geometry and contact parameters [3]:

$$s = k \cdot \frac{l_n}{h_1}, \quad (2)$$

where l_n – is the distance from the neutral section to the exit plane; h_1 – is the final strip thickness; k – is a coefficient that accounts for friction, temperature, and the rheology of the material.

Accurate calculation of sss is critical for determining the length of the deformation zone and ensuring geometric consistency of the billet between successive passes. An error in estimating forward slip leads to a discrepancy between the actual and the calculated product length, which prevents precise alignment of the roll grooves in subsequent rolling stages and may result in defects.

According to the studies of S. O. Skriabin [1], forward slip depends on the following factors: the degree of deformation; the billet temperature;the strip width; the final height of the rolled profile.

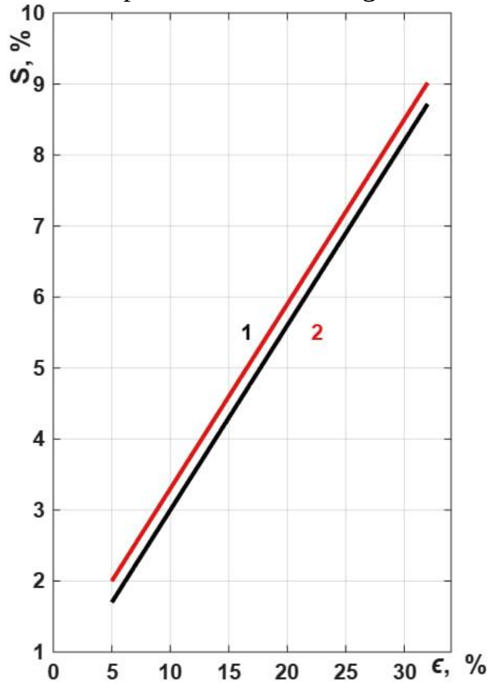

Fig. 1. Dependence of forward slip on the degree of deformation and billet temperature in smooth rolls: 1 – 250 °C; 2 – 450 °C.

Figure 1 shows that forward slip increases with higher reductions; as the metal temperature rises, forward slip decreases due to the reduction of the friction coefficient and the increase in metal plasticity.

This is consistent with the analytical formula proposed by Ekelund [4]:

$$s = \frac{\mu l}{h_1}, \quad (3)$$

where μ – is the friction coefficient, l – is the length of the deformation zone, h_1 – is the final strip thickness.

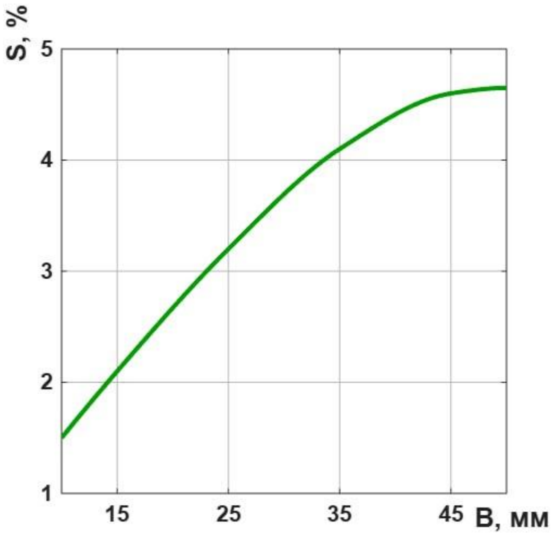

Fig. 2. Dependence of forward slip on billet diameter. Reduction degree: 30%

The data for the AK6 alloy at $\varepsilon = 20\%$ (Fig. 2) show that with increasing initial billet diameter, forward slip increases almost linearly up to ≈ 40 mm, after which the growth rate decreases. This occurs because the lateral spread decreases with increasing diameter, and according to the law of volume constancy:

$$\Delta V = 0 \Rightarrow \Delta l \sim f(\Delta h, \Delta b), \tag{4}$$

as the lateral spread decreases, elongation increases, and consequently forward slip also increases.

To determine the influence of roll temperature, rolling tests were carried out on AK6 alloy samples with diameters of 14–25 mm at ε=30–50 and a metal temperature of 450 °C [1]. The roll temperature was varied in the range of 20–450 °C.

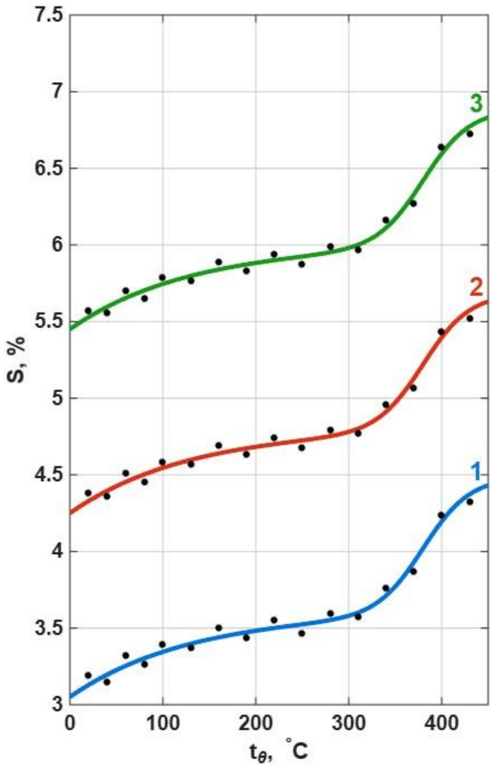

Fig. 3. Dependence of forward slip on the degree of deformation and roll-heating temperature (deformation degrees: 1 – 30%; 2 – 40%; 3 – 50%; billet heating temperature: 450 °C)

Analyzing the established dependencies (Fig. 3) of forward slip on the degree of deformation and roll-heating temperature, it can be observed that:

• increasing the roll temperature to 250 °C raises forward slip to 14–16% (depending on ε);

• within the range of 200–350 °C, the change is minor – forward slip becomes stabilized;

• further heating to 450 °C results in an additional increase in forward slip by 28–47%, which is associated with a reduction in friction and the intensification of recrystallization processes.

This behavior is explained by the decrease in the friction coefficient with increasing temperature:

$$\mu = \mu_0 e^{-Q/(RT)}, \quad (5)$$

where μ_0 is the pre-exponential factor; Q is the activation energy of sliding; R is the universal gas constant; T is the temperature in the contact zone.

Overall, the following regularities are observed:

• increasing the billet and roll temperatures → reduced friction → increase in s;
• increasing the degree of deformation → more intensive forward slip → increase in s;
• within the range of 200–350 °C → the influence of roll temperature is minimal.

5. Conclusion

The conducted research has established the regularities of forward slip formation during the hot rolling of the AK6 aluminum alloy. The magnitude of forward slip is significantly influenced by billet and roll temperatures, the degree of deformation, and sample geometry, which confirms the complex kinematic nature of the hot deformation process.

A comparison of hot and cold rolling revealed a fundamental difference in the mechanisms of forward slip formation. Under cold deformation, forward slip is lower and exhibits a more stable dependence on reduction due to the high friction coefficient and pronounced work hardening. In contrast, during hot rolling, the reduction in flow stress, activation of dynamic recovery and recrystallization, and the decrease in friction coefficient lead to a substantial increase in forward slip.

It was found that forward slip increases with a higher degree of deformation for all investigated rolling regimes. Increasing the reduction from ε=30%\varepsilon = 30\%ε=30% to 40% and 50% results in a rise in forward slip by 49.7% and 77.68%, respectively, which is consistent with the volume constancy law and the proportional increase in billet elongation.

The temperature factor plays a key role in forward slip formation. Raising the roll temperature to 250 °C increases forward slip by 12–16%, while heating the rolls to 450 °C yields an increase of 28–47%, depending on the degree of deformation. This effect is associated with a decrease in friction, enhanced metal plasticity, and a more uniform redistribution of stresses in the contact zone.

Within the temperature range of 200–350 °C, forward slip becomes stabilized at a constant degree of deformation. This behavior is attributed to the equalization of axial compressive stresses and the similarity of elongation and spread values, which reduces the influence of roll temperature variations on process kinematics.

The influence of the initial billet diameter on forward slip is nonlinear. For the AK6 alloy, it was established that increasing the diameter up to 40 mm leads to an almost linear rise in forward slip, whereas further increase results in slower growth. This is caused by reduced lateral spread and a more balanced metal flow in the deformation zone.

The experimental results show good agreement with classical analytical models proposed by Pavlov, Ekelund, Fink, and Dresden–Golovin, which allows their application in engineering calculations for hot rolling of the AK6 alloy, with consideration of correction factors for high-plasticity temperature ranges.

The findings have practical significance for optimizing the technology of hot rolling of aluminum products. They enable more accurate prediction of the deformation zone length, reduce errors in groove design, ensure the precision of geometric parameters of the rolled products, and improve the overall efficiency of the production process.

References

1. Skriabin, S. O. (2018). *Investigation of kinematic parameters of hot rolling of aluminum alloys*. Metaloobrobka ta OTT. [in English].
2. Roberts, W., & Hirsch, J. (2010). *Fundamentals of rolling*. Elsevier. [in English].
3. Ekelund, C. (1999). Slip ratio in hot rolling: Analytical approximations. *Journal of Materials Processing Technology*. [in English].
4. Golovin, A. (2007). *Deformation mechanics in contact zones under rolling*. Springer. [in English].
5. Sevidov, A. E., & Muntin, A. V. (2021). Determination of the friction coefficient during hot strip rolling under industrial conditions using forward slip. In *METAL 2021 – 30th International Conference on Metallurgy and Materials*. DOI: https://doi.org/10.37904/metal.2021.4103 [in English].

6. Shtuts, A., Kolisnyk, M., Vydmysh, A., Voznyak, O., Baraban, S., & Kulakov, P. (2020). Improvement of stamping by rolling processes of pipe and cylindrical blades based on experimental research. *Key Engineering Materials, 844,* 168–181. . DOI: https://doi.org/10.4028/www.scientific.net/KEM.844.168 [in English].
7. Solona, O., Derevenko, I., & Kupchuk, I. (2019). Determination of plasticity for a pre-deformed billet. *Solid State Phenomena, 291*, 110–120. . DOI: https://doi.org/10.4028/www.scientific.net/SSP.291.110 [in English].
8. Haydamak, O. L. (2023). Regularities of plasticity reserve restoration and a method for its calculation during deformation with intermediate heat treatment. *Metallophysics and Advanced Technologies, 45*(10), 1189–1204. [in English].
9. Haydamak, O. L., & Hraniak, V. F. (2024). Study of the processes of forming a metal coating by cold gas dynamic sputtering and development of a technique for calculating sputtering modes. *Metallofizika i Noveishie Tekhnologii*, *45*(12), 1485–1498. . DOI: https://doi.org/10.15407/mfint.45.12.1485 [in English].
10. Voznyak, O., Polievoda, Y., Kupchuk, I., Trukhanska, O., Shvets, L., & Zamrii, M. (2023). Development of an object detection algorithm in halftone images. *Przegląd Elektrotechniczny, 99*(11), 192–195. [in English].
11. Shvets, L. V., & Chmykh, K. V. (2024). Investigation of metal flow of AK6 aluminum alloy on a modernized hot rolling installation. *Tekhnika, Enerhetyka, Transport APK, 126*(3), 23–35. . DOI: https://doi.org/10.37128/2520-6168-2024-3-3 [in English].

ДОСЛІДЖЕННЯ ВИПЕРЕДЖЕННЯ ПРИ ГАРЯЧОМУ ПРОКАТУВАННІ АЛЮМІНІЄВОГО СПЛАВУ АК6

У статті представлено результати комплексного дослідження випередження під час гарячого прокатування деформівного алюмінієвого сплаву АК6. Випередження, яке характеризує різницю між окружною швидкістю валків та фактичною швидкістю виходу металу із зони деформації, є ключовою кінематичною величиною, що визначає точність розрахунку довжини деформованої ділянки й забезпечує правильне узгодження послідовних переходів технологічного процесу. Незначна похибка у визначенні цього параметра може призвести до накопичення геометричних відхилень, порушення роботи калібрів та виникнення браку на наступних стадіях обробки.

Метою дослідження є визначення закономірностей зміни випередження залежно від температурних умов прокатування, ступеня деформації, геометричних характеристик заготовки та температури нагрівання валків. Для цього проведено серію експериментів із прокатування зразків алюмінієвого сплаву АК6 діаметром 14–25 мм при обтисненнях 30, 40 та 50 % у гладких валках з регульованою температурою. Заготовки нагрівали до 450 °С, а температуру валків змінювали в діапазоні 20–450 °С. У процесі реєстрували величину випередження та здійснювали порівняльний аналіз із відомими аналітичними моделями Павлова, Фінка, Екелунда та Дрездена–Головіна.

Результати показали, що зі збільшенням ступеня обтиснення випередження закономірно зростає, що пов'язано зі збільшенням подовження та перерозподілом швидкостей у приповерхневих шарах. Підвищення температури заготовки й валків призводить до зменшення коефіцієнта тертя, зростання пластичності металу та активізації процесів динамічного повернення й рекристалізації, що спричиняє збільшення випередження. Встановлено, що у температурному інтервалі 200–350 °С за фіксованої редукції вплив нагріву валків мінімальний, і випередження змінюється незначно. Проте подальше підвищення температури до 450 °С дає суттєве зростання параметра, до 47 % залежно від ступеня деформації.

Отримані залежності дозволяють оцінювати вплив ключових технологічних параметрів на кінематичну поведінку сплаву АК6 та забезпечують підвищення точності прогнозування геометричних характеристик у процесі гарячого прокатування. Результати можуть бути використані під час оптимізації режимів обтиснення, температурної підготовки заготовок і прокатних штампів, а також у розрахункових моделях деформації алюмінієвих сплавів.

Ключові слова: *заготовка, деформація, деформаційне протягування, пластична деформація, інтенсивність деформацій, напружено-деформований стан, пластичність, технологічний процес, алюмінієві сплави.*

Ф. 5. Рис. 3. Літ. 11.

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