Journal of Chemical Technology and Metallurgy, 61, 3, 2026, 529-538

COMPUTER MODELING AND RESEARCH OF THE ASYMMETRIC ROLLING OF A WORKPIECE WITH A GRADIENT DISTRIBUTION OF MECHANICAL PROPERTIES

Abdrakhman Naizabekov[1], Evgeniy Panin[2], Sergey Lezhnev[3],
Ilya Chumanov[4], Andrey Anikeev[4], Alexandr Arbuz[5], Sergey Kuzmin[3],
Valery Chigirinsky[3], Pavel Tsyba[2], Sergey Rovin[6]

[1]Science, Education and Staff Planning LLP
Astana, Kazakhstan, naizabekov57@mail.ru (A.N.)
[2]Karaganda Industrial University, Temirtau
Kazakhstan, ye.panin@tttu.edu.kz (E.P.); tpl-work@mail.ru (P.T.)
[3]Rudny Industrial University, Rudny
Kazakhstan, sergey_legnev@mail.ru (S.L.); decan_2008@mail.ru (S.K.);
chigirinvv18@gmail.com (V.C.)
[4]South Ural State University, Chelyabinsk
Russia, chumanoviv@susu.ru (I.C.); anikeevan@susu.ru (A.An.)
[5]Nazarbayev University, Astana
Kazakhstan, zubra_kz@mail.ru (A.Ar.)
[6]Almalyk Branch of MISiS, Almalyk
Uzbekistan, rovinsl@mail.ru (S.R.)

Received 20 January 2026
Accepted 10 March 2026
DOI: 10.59957/jctm.v61.i3.2026.15

ABSTRACT

The paper presents the results of finite-element modelling of asymmetric rolling of a workpiece with a gradient distribution of mechanical properties. To create a gradient distribution of properties, the workpiece was pre-loaded and Vickers microhardness was evaluated. The resulting workpiece model had a microhardness distribution that was close to the experimental values. The workpiece was subjected to both symmetric rolling and asymmetric rolling with an asymmetry coefficient of 1.5, which was achieved by varying the roll speeds (90 and 60 rpm) in two scenarios (90/60 and 60/90). The parameters of the stress-strain state and the rolling force were analyzed. The results showed that asymmetric rolling of a workpiece with a gradient distribution of mechanical properties had only minor differences from symmetric rolling. When the asymmetry coefficient exceeds 3, this factor begins to have a significant impact on the processing unevenness.

Keywords: asymmetric rolling, mechanical properties, gradient distribution, Vickers microhardness, stress-strain state, rolling force.

INTRODUCTION

Traditionally, the mechanical properties of the steels and alloys used in the ferrous metallurgy industry are improved by adding a significant number of alloying elements to the metal or alloy. Currently, the existing grades are more than sufficient to meet the current needs of the industry. However, an analysis of the market prices for alloying elements reveals that the prices for ferroalloys are increasing every year.

An alternative to using expensive alloying elements is the use of heterophase dispersed-reinforced steels, including those with an undifferentiated layer boundary, which are produced using various technologies for injecting ultrafine particles into the crystallizing melt to achieve gradient mechanical properties. These steels are representative of modern materials, as they utilize a rational design approach to provide the necessary properties only to those areas that require them.

For this reason, it is a very relevant task not only to develop new technologies for producing heterophase dispersed-reinforced steels with an undifferentiated interface between the layers, but also to develop technologies for processing them by pressure, as in some cases it is impossible to use a simple cast billet. A comprehensive solution to the above-mentioned task will allow to obtain new materials that meet the specific requirements of the existing industry, while also having a relatively low cost, which can be achieved by using a small amount of properly selected ultrafine powders, which can be placed on the working surface or in other volumes of the product that requires specific properties.

Now, several promising methods for injecting ultrafine particles into a crystallizing melt have already been developed and studied by various scientific teams, including the method of introducing dispersed particles during centrifugal casting, which allows for the production of heterophase dispersed-reinforced steels with an undifferentiated interface between the layers [1 - 6].

The most effective method for deforming heterophase dispersed-reinforced steels with an undifferentiated layer boundary, which initially have a gradient distribution of properties along the thickness, is asymmetric rolling [7]. In conventional symmetric rolling, where both rolls exert the same force on the workpiece, the workpiece will receive uniform deformation across its entire cross-section after each deformation cycle. As a result, the gradient of all properties will remain unchanged as the overall level of accumulated deformation increases. However, in asymmetric rolling, the influence of each roll on the workpiece's deformation will vary depending on the asymmetry coefficient. Consequently, as the overall level of accumulated deformation increases, it will be possible to either increase or decrease the gradient of properties, resulting in a more uniform distribution of properties along the thickness.

For deformation processing of workpieces made of heterophase dispersed reinforced steels with an unexpressed interface of layers that initially have a gradient distribution of properties over thickness, the most effective method is asymmetric rolling [7]. Thus, with conventional symmetrical rolling, when the effect of both rolls on the workpiece is the same, after each deformation cycle, the workpiece will receive a uniform treatment over the entire section. As a result, as the overall level of accumulated strain increases, the gradient of all properties will be maintained. With asymmetric rolling, the effect of each roll on the workpiece processing will differ depending on the asymmetry coefficient. As a result, with an increase in the overall level of accumulated strain, it will be possible to both increase and decrease the gradient of properties, bringing the distribution of properties over the thickness to a more uniform state.

Asymmetric rolling has been known for quite a long time. Scientists from various countries have studied various options for implementing asymmetric rolling in practice and its impact on the quality of rolled thick-sheet metal [8 - 13]. However, in most cases, the initial billets before asymmetric rolling had a uniform distribution of properties across the thickness of the metal. The process of asymmetric rolling of a billet made of dispersed-reinforced steel with an undifferentiated layer boundary has not been studied previously. Although there are known options for asymmetric rolling of bimetallic billets, which, like in our case, have a gradient of properties across the thickness, but only with a distinct layer boundary [14 - 17].

The purpose of this work is to perform computer modelling and study the process of asymmetric rolling of a billet with a gradient of mechanical properties across the thickness, which was achieved by introducing dispersed particles into the crystallizing melt during centrifugal casting.

EXPERIMENTAL

In recent years, modern software systems for finite element modeling of metal forming processes (DEFORM, QFORM, Simufact Forming, LS Dyna) have significantly expanded their functional capabilities. Almost every year, new versions of these products are released, incorporating new features such as improved finite element mesh generators and new material plasticity models. As a result, end users could explore new and existing metal forming processes at a higher level of sophistication.

However, despite these advantages, all these programs also have limitations that are directly related to the fundamental principles of modelling. The resulting model is not the final, real-world outcome.

It is impossible to obtain a model with zero error, as there are always numerous factors in a physical experiment that cannot be accounted for in the modelling process. The biggest assumption in modelling is the material tolerance, which is assumed to be completely isotropic and perfect, without any internal defects or inhomogeneities. For most metal forming processes, this assumption is acceptable, as the focus is often on the impact of the plastic deformation process on the cross-sectional development of the workpiece. In such cases, it is preferable to use a homogeneous workpiece, which can be achieved through pre-annealing in a physical experiment.

This principle is unsuitable for studying workpieces obtained by introducing dispersed particles during centrifugal casting. Such workpieces initially have a spread of mechanical properties across their cross-section, and subsequent deformation will result in significantly different outcomes compared to the deformation of a homogeneous workpiece. Therefore, it is necessary to first obtain a model of the initial workpiece that corresponds to the actual conditions of introducing dispersed particles into the crystallizing melt during centrifugal casting. To achieve this, the final experimental results can be used as initial data for modelling.

The experimental results of Vickers hardness measurements (Fig. 1a) were used as initial data for modelling. The tests were conducted on 08X18N10T stainless steel under a load of 0.5 kgf for 15 s. As can be seen from the hardness distribution graph in Fig. 1b, there are three distinct zones along the thickness of the workpiece: the outer zone has the lowest hardness, the intermediate zone is the most extensive (50 - 60 % of the total thickness), and the hardness level is approximately 30 % higher than in the outer layer. The final zone (the inner layer) has the highest hardness, which is 58 % higher than in the outer layer.

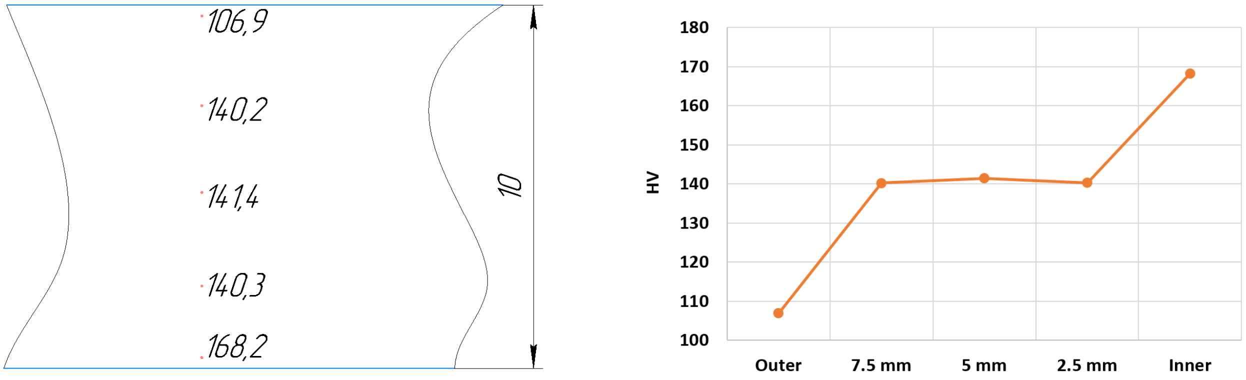
To obtain such a property distribution, the workpiece must be subjected to uneven deformation. However, there is also a problem of comparing the simulation results with experimental data. The DEFORM software used has a built-in hardness analyser that works on the Rockwell C scale (HRC). However, in our case, it is unsuitable because the translation scale does not have values in the corresponding range of both scales.

Therefore, the only correct option in this case is to simulate a Vickers hardness test by measuring the diagonal of the pyramid imprint. To create a scheme of uneven deformation, it was decided to use the pressing process with certain boundary conditions:

- the free flow of metal occurred only in one direction;

- the contact conditions on the horizontal surfaces were different - on one surface, the coefficient of friction was low (0.15, which corresponds to a polished surface with lubrication), while on the other surface, the coefficient of friction was high (1, which corresponds to a rough textured surface).

These conditions can be implemented in practice by pressing the workpiece in a U-shaped tool (Fig. 2), with the lower plate having a textured surface to create



a)

b)

Fig. 1. Distribution of Vickers hardness along the workpiece thickness (a) and hardness graph (b).

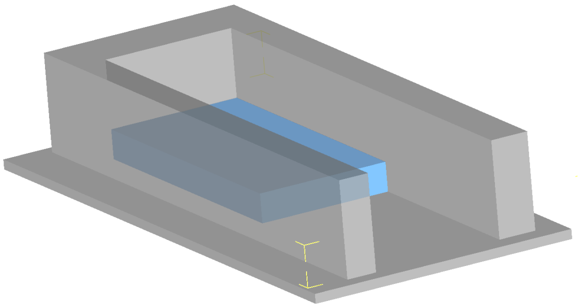


Fig. 2. Upsetting model in U-shaped tool for creating an uneven metal flow.

a high level of adhesion to the workpiece.

The next task is to determine the level of upsetting to achieve the required level of metal processing. Here, the key parameter will be the value of equivalent strain, which, for a given material, will lead to a specific level of hardening. Since it is extremely difficult to calculate this analytically, it was decided to build several models, in each of which a workpiece of different thicknesses, from 11 to 20 mm, was drawn down to 10 mm.

The final task was to determine the most optimal model, not only based on the hardness values, but also on their distribution across the workpiece thickness. To achieve this, it is necessary to enter the initial hardness value in the material database, which will correspond to the initial (undeformed) state. By default, the AISI 304 steel (equivalent to 08X18N10T steel) has a hardness of 129 HV, which is lower than the obtained value in the outer layer. This may be due to the occurrence of a certain level of porosity during casting. In this case, it is advisable to set the hardness value of 106.9 HV as the initial value.

After a sequential analysis of the obtained drawing models, it was revealed that the most suitable results were obtained when drawing workpieces with a thickness of 14 - 15 mm. The workpiece receives an uneven development across its thickness (Fig. 3). Here, two patterns of strain distribution are shown: a global pattern and a local pattern in the range of 0 - 3, to assess the strain level in the upper layer.

When simulating the hardness test, a force of 4.903 N was applied to the pyramid, which corresponds to a load of 0.5 kgf. As a result, the pyramid was embedded in the workpiece, resulting in a diagonal length of 0.0937 mm (Fig. 5). According to GOST R ISO 6507-4-2009 "Metals and Alloys. Vickers Hardness Measurements. Part 4. Tables for Determining Hardness", this diagonal value corresponds to a hardness value of 105.5 HV approximately.

Further hardness measurement results are presented in Table 1. Fig. 5 shows the summary hardness values obtained during the experiment and modelling. Comparing these values, we can conclude that the obtained model adequately describes the mechanical state of 08X18N10T steel after centrifugal casting.

To assess the impact of the initial property dispersion on the subsequent metal state during deformation, it was decided to conduct the simulation in three directions:

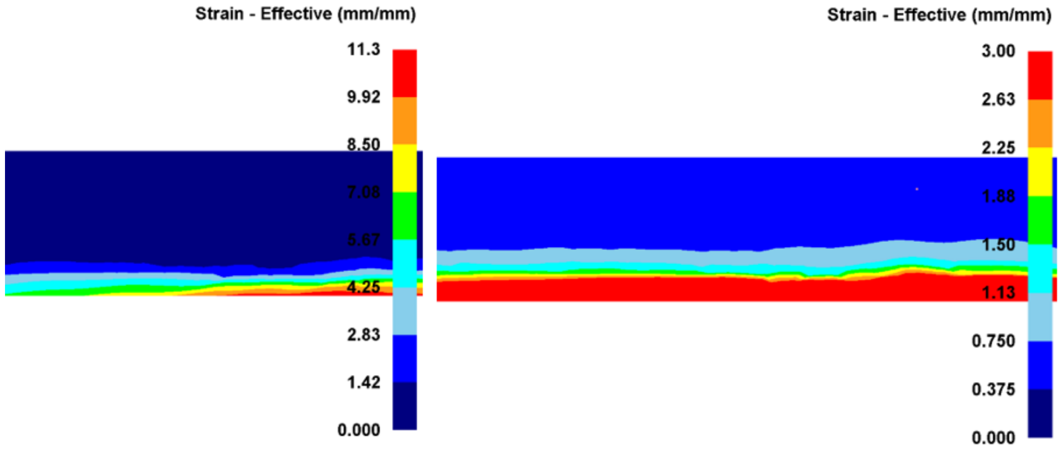


Fig. 3. Uneven strain during the upsetting of a 15 mm thick workpiece.

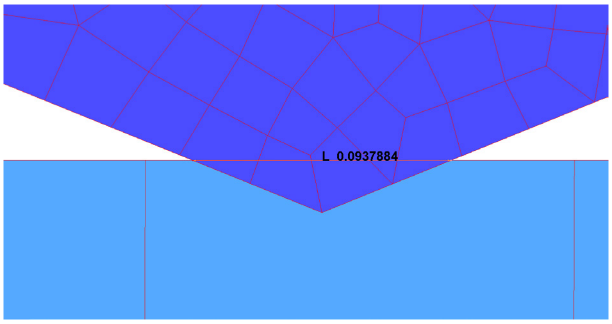


Fig. 4. Hardness measuring on the outer layer.

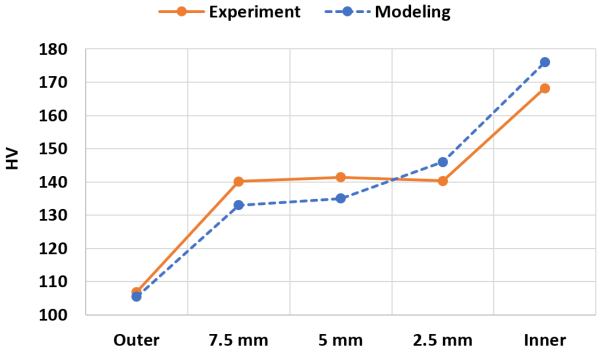


Fig. 5. Comparative graph of hardness values.

Table 1. Hardness measurement results.

Place of measurement	Print diagonal, mm	Hardness, HV
Outer layer	0.0937	105.5
7.5 mm	0.0835	133
5 mm	0.0831	135
2.5 mm	0.0798	146
Inner layer	0.0726	176

1) symmetric rolling in smooth rolls;

2) asymmetric rolling in smooth rolls (asymmetry effect on the outer layer);

3) asymmetric rolling in smooth rolls (asymmetry effect on the inner layer).

In addition, the asymmetric rolling process was considered in two variants: kinematic and geometric, with the same level of asymmetry. These models allow for the evaluation of the workpiece's cross-sectional development under different loading conditions.

Since the rolling process is conducted in smooth rolls with a small reduction, the simulation can be performed in a 2D mode. The roll diameter is 200 mm. The workpiece is a rectangular sheet with a thickness of 10 mm and a length of 100 mm. AISI 304 steel (like 08X18N10T steel) was chosen as the material for the workpiece, which was previously used in the creation of the initial workpiece. The following technological parameters were used in the computer simulation of the process:

- the workpiece material was anisotropic, and the property dispersion was obtained in the previous step;

- the rolling process was conducted at an ambient temperature of 20°C;

- the heating temperature of the workpiece before rolling was set to 900°C and 1100°C;

- the heat transfer coefficient between workpiece and tool was 5000 W m^{-2} °C^{-1};

- heat transfer coefficient between workpiece and environment was 0.002 W m^{-2} °C^{-1};

- the coefficient of friction between the metal and the rolls was assumed to be 0.4 (corresponding to a surface with a high level of roughness);

- the rotational speed of the rolls during symmetric rolling was set to 60 rpm; during kinematic asymmetric rolling, the rotational speeds of the rolls were set to 60 rpm and 90 rpm (with an asymmetry coefficient of 1.5);

- the geometric asymmetry model was achieved by varying the roll diameters (200 mm and 300 mm), with a rotational speed of 60 rpm on both rolls.

RESULTS AND DISCUSSION

To analyse the calculated models, the workpiece shape in the deformation zone of the rolling rolls was considered, as well as the key parameters of the stress-strain state that most accurately characterize the effect of the deformation scheme on the metal processing. These parameters include equivalent strain, average hydrostatic pressure, and deformation force. Fig. 6 shows the results of the workpiece's deformation in all the considered models.

In general, the workpiece forming is fully consistent with the principle of asymmetric rolling, where higher values of linear velocity are created on the faster roll in contact with the workpiece. As a result, these layers significantly outpace the layers in contact with the other roll, leading to a workpiece bending in the opposite direction. Similar shape changes were observed in various types of asymmetric rolling. However, in practice, the most effective scheme is kinematic asymmetry, which can be achieved by using individual roll drives with frequency converters. This allows for the adjustment of the asymmetry level in any range. In contrast, geometric asymmetry is limited by the maximum diameter of the rolls that can be accommodated in the corresponding machine frame. As a result, the maximum asymmetry level is often limited to 2. Therefore, it was decided to focus on kinematic asymmetry in the following analysis.

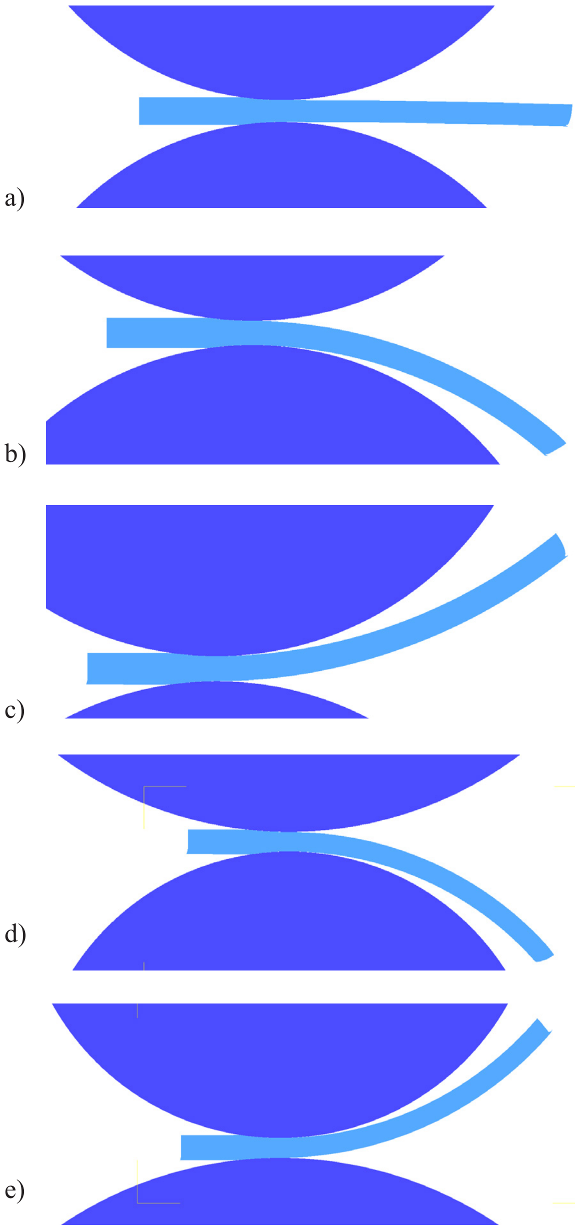


Fig. 6. Workpiece forming: (a) symmetric rolling; (b) kinematic asymmetric rolling with the asymmetry effect on the upper outer layer (90/60); (c) kinematic asymmetric rolling with the asymmetry effect on the lower inner layer (60/90); (d) geometric asymmetric rolling with the asymmetry effect on the upper outer layer (300/200); (e) geometric asymmetric rolling with the asymmetry effect on the lower inner layer (200/300).

For a more in-depth analysis, it is necessary to consider the main parameters of the stress-strain state, as well as the deformation force. When evaluating the stress state, the most effective parameter is the average hydrostatic pressure, which indicates the level of stress, considering the sign, i.e., the magnitude of tensile and compressive stresses. This parameter is determined by the Eq. (1):

$$\sigma_{AV} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \qquad (1)$$

where σ_1, σ_2, σ_3 - principal stresses.

When assessing the strain state, the most effective parameter is the equivalent strain, which shows the accumulated level of strain at a specific point. This parameter is calculated using the Eq. (2):

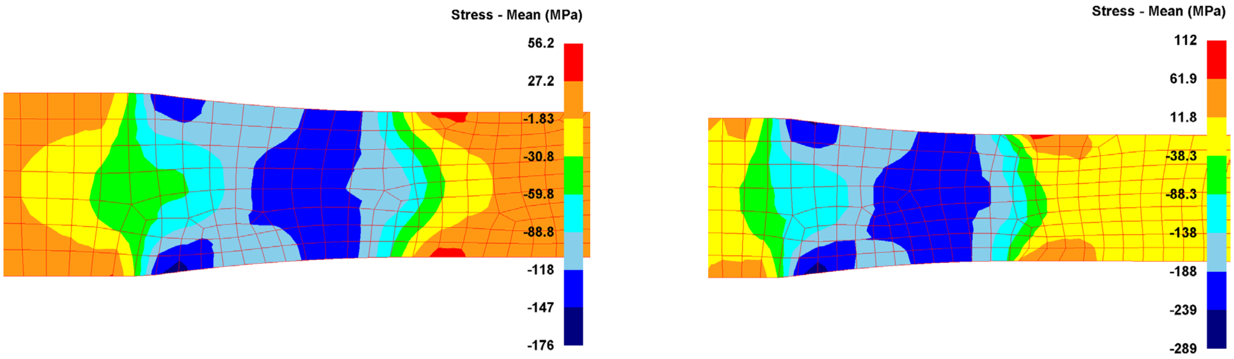
$$\varepsilon_{EQV} = \frac{\sqrt{2}}{3}\sqrt{\left(\varepsilon_1 - \varepsilon_2\right)^2 + \left(\varepsilon_2 - \varepsilon_3\right)^2 + \left(\varepsilon_3 - \varepsilon_1\right)^2} \qquad (2)$$

where ε_1, ε_2, ε_3 - principal strains.

Fig. 7 shows the average hydrostatic pressure patterns in the deformation zone of the rolling rolls for symmetric rolling models at different temperatures.

The stress distribution in both cases is identical, but reducing the heating temperature by 200°C increases the compressive stress by more than 1.5 times. The tensile stress also increases by almost half, but its level and coverage area are significantly lower than the compressive stress. The stress distribution is symmetrical in both cases.

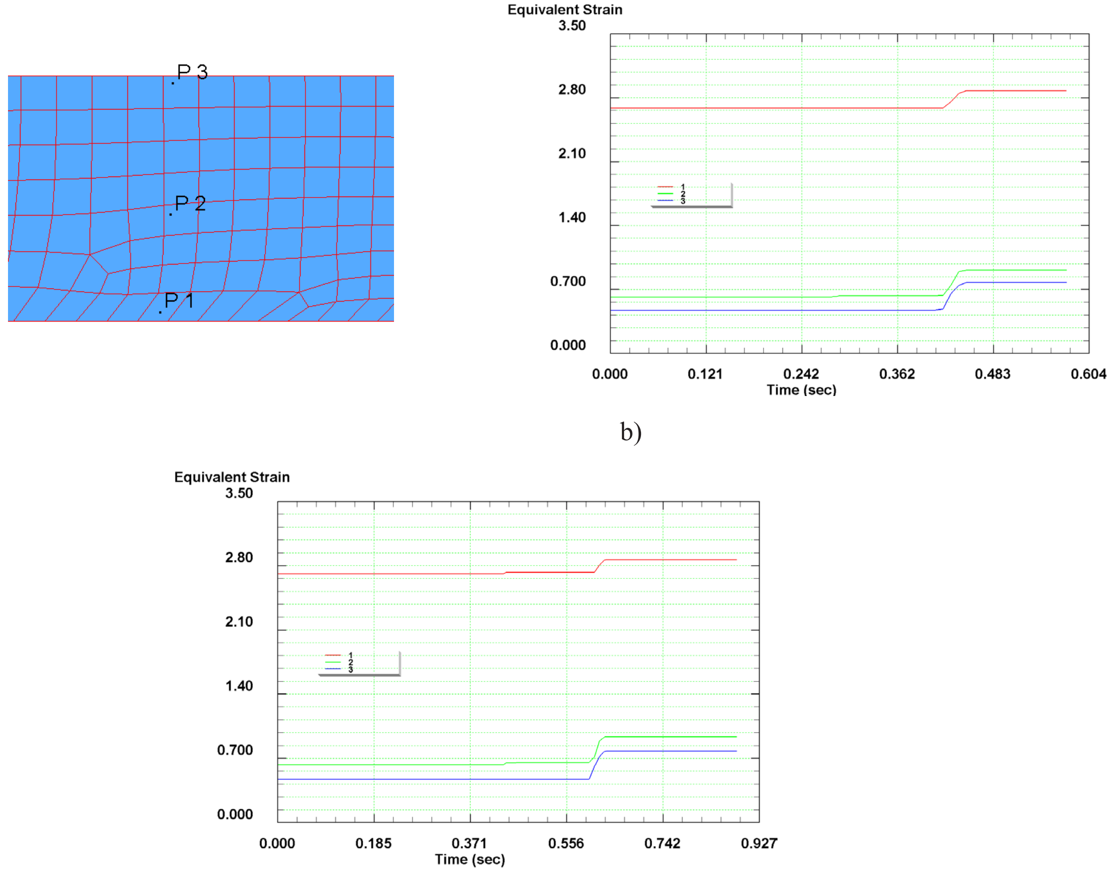
It would be inefficient to consider equivalent deformation in this way, as the workpiece has a wide range of values. Therefore, the principle of tracking the parameter at specific points was applied (Fig. 8a). Point 1 corresponds to the hardened inner layer, point 2



a)

b)

Fig. 7. Average hydrostatic pressure in the deformation zone of rolling rolls: (a) 1100°C; (b) 900°C.



a)

b)

c)

Fig. 8. Equivalent strain: (a) specified points along the workpiece height; (b) graph of strain change at 1100°C; (c) graph of strain change at 900°C.

corresponds to the central layer, and point 3 corresponds to the least hardened outer layer. The measurement results for the model with a workpiece temperature of 1100°C are presented in Fig. 8b.

The graph shows that the strain increases by approximately 15 % along the entire height of the workpiece after rolling. When the temperature is reduced to 900°C (Fig. 8c), there are no significant differences in the growth pattern or strain values at any of the specified points. When analysing the rolling forces, it was found that reducing the heating temperature significantly increases the rolling force. For example, the initial rolling force of 3.08 kN for a model with a workpiece temperature of 1100°C increased to 5.08 kN when the temperature was reduced to 900°C.

This low value of force is the result of modelling in a flat state (2D), where the workpiece width is 1 mm. To obtain an accurate value of force, these values must be multiplied by the actual width. It is important to note that the force distribution on the rolls is identical in these models, indicating that the initial gradient of properties has a small impact on symmetric deformation.

When considering asymmetric rolling models, it is convenient to analyse all four models simultaneously to assess the combined effects of asymmetry and temperature. To accurately evaluate the average hydrostatic pressure in comparison with symmetric options, it is necessary to present the results in the same dimensional scales (Fig. 9).

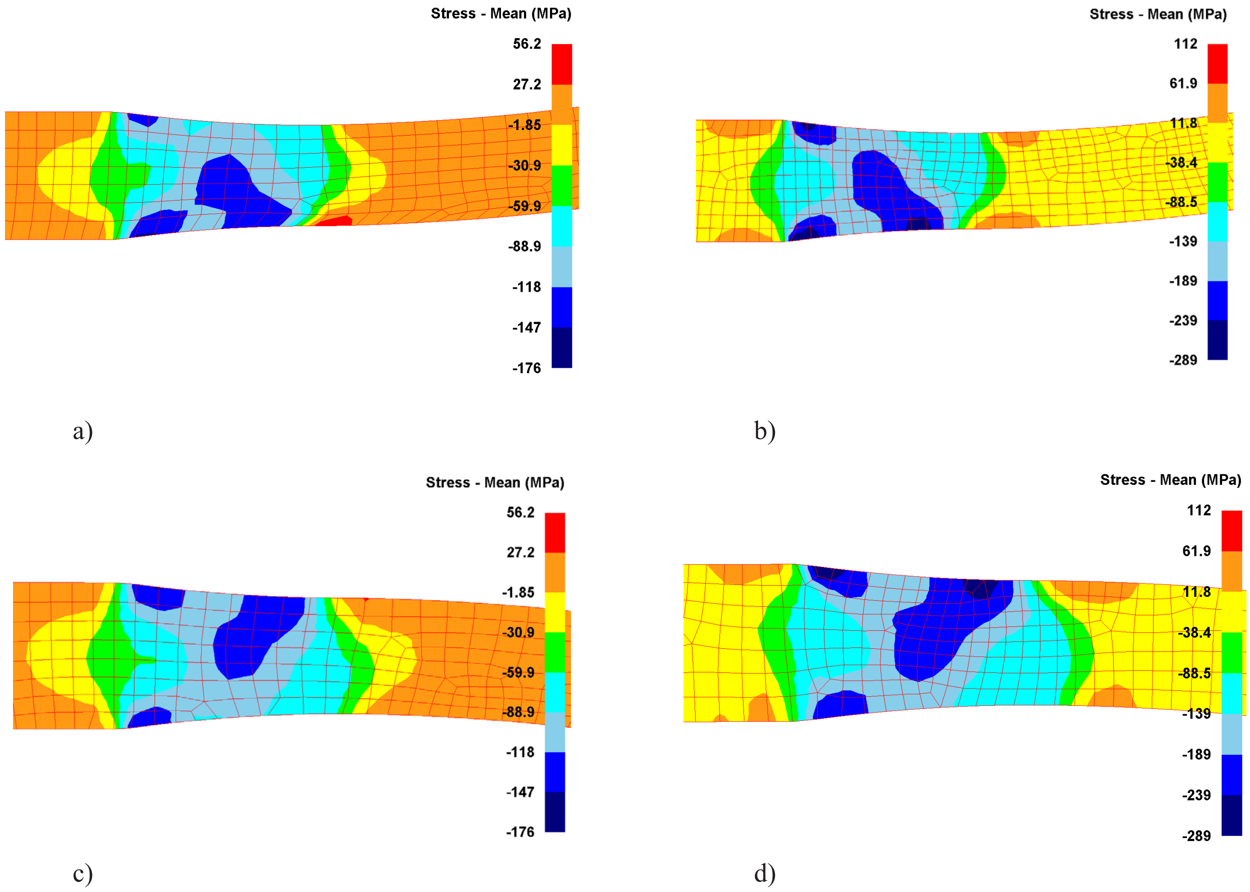
There are two key points to note here:

1) as the temperature decreases in both cases, as well as in symmetric rolling, the stress distribution remains constant;

2) the introduction of the asymmetry factor disrupts the symmetry of the deformation zone, leading to an increase in compressive stresses at the contact with the faster roll. On the opposite roll, the level of stresses decreases. In this case, the asymmetric stress distribution is a mirror image when the direction of asymmetry is reversed.

To assess the strain state, the values of equivalent strain were examined at the three previously defined points (Table 2).

Based on the analysis of the obtained data, it can be concluded that the asymmetric scheme has a minor effect on the deformation of the gradient billet. The most significant changes were observed at point 1 (the hard inner layer), while no significant changes were observed



a) b) c) d)

Fig. 9. Average hydrostatic pressure during asymmetric rolling: (a) model 60/90 at 1100°C; (b) model 60/90 at 900°C; (c) model 90/60 at 1100°C; (d) model 90/60 at 900°C.

Table 2. Maximum values of equivalent strain.

Point	Symmetric rolling 1100°C	Symmetric rolling 900°C	60/90 1100°C	60/90 900°C	90/60 1100°C	90/60 900°C
1	2.87	2.87	2.95	2.9	3.08	3.06
2	0.805	0.805	0.805	0.805	0.98	0.96
3	0.77	0.77	0.77	0.77	0.84	0.84

Table 3. Average values of forces, N.

Symmetric rolling 1100°C	Symmetric rolling 900°C	60/90 1100°C	60/90 900°C	90/60 1100°C	90/60 900°C
3080	5080	3020	5420	3050	5300

at points 2 and 3. However, it should be noted that the use of a relatively low level of asymmetry (1.5) may have influenced the results. In some studies, on asymmetric rolling, the effects of higher levels of asymmetry on metal processing have been reported. Therefore, it is advisable to conduct additional research on the effects of higher levels of asymmetry using the most distinct scheme (90/60 at 1100°C). Table 3 presents the average values of the forces during asymmetric deformation.

By analysing the obtained data, it is possible to confirm the previously made conclusion about the insignificant effect of the asymmetric scheme during the deformation of a gradient workpiece. In all the considered cases of asymmetric rolling, the values of the forces do not differ significantly from those of symmetric rolling. The most noticeable differences are observed in models with lower temperatures, which is a result of increased compressive stresses in the roll deformation zone.

The final stage of the research was to study the impact of increased asymmetry levels on the metal processing. When analysing point 1 (the hard inner layer), it was found that as the asymmetry factor increases, the level of strain also increases. For example, at an asymmetry level of 3, the maximum equivalent strain was 3.22, while at an asymmetry level of 6, the maximum equivalent strain was 3.48.

CONCLUSIONS

The presented results of finite-element modelling of rolling a workpiece with a gradient distribution of mechanical properties showed that when asymmetric rolling is implemented with a small asymmetry coefficient, the overall pattern of metal processing with a gradient distribution of properties is similar to that of a symmetric scheme. However, when the asymmetry coefficient exceeds 3, this factor begins to have a significant impact on the unevenness of metal processing. Therefore, to control the processing of metal with a gradient distribution of mechanical properties, it is necessary to use asymmetric rolling with a high asymmetry level.

Acknowledgements

This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant № AP23485709).

Authors' contributions

E.P.: investigation, writing - original draft; P.T.: methodology; A.N.: investigation, funding acquisition, project administration; S.L.: conceptualization, methodology, investigation; S.K.: visualization, investigation; V.C.: validation, data curation; I.C.: software; A.An.: writing - review & editing; A.Ar.: resources; S.R.: formal analysis.

REFERENCES

1. S.A. Guzenkov, D.N. Fedorov, D.V. Rutskii, S.B. Gamaniuk, Increasing the structural strength of cast steel by modifying it with dispersed powders, Steel, 3, 2010, 101-103, (in Russian).
2. E.V. Protopopov, V.P. Komshukov, L.A. Ganzer, D.B. Foyg, Promising technologies for modifying

metal with nanopowder inoculants, Bulletin of Scientific, Technical, and Economic Information “Ferrous Metallurgy”, 6, 2011, 39-44, (in Russian).

3. S.N. Zherebtsov, V.I. Gurdin, Electroslag casting of parts made of 08Kh18N10T steel, Mechanical Engineering Technology, 7, 2005, 44-52, (in Russian).
4. I.V. Chumanov, D.A. Pyatygin, E.E. Telyanova, A.N. Anikeev, Method of continuous casting of blanks, RU Patent 2080206, 2007, (in Russian).
5. I.V. Chumanov, V.I. Chumanov, D.A. Pyatygin, E.E. Telyanova, Increasing the wear resistance of steel by introducing titanium carbide during the crystallization of the ingot, Electrometallurgy, 2, 2008, 32-35, (in Russian).
6. I.V. Chumanov, A.N. Anikeev, D.A. Zherebtsov, Influence of dispersed tungsten carbide particles on the microstructure of 12Kh18N10T steel obtained by centrifugal casting, Ferrous Metals, 12, 2020, 68-73, (in Russian).
7. Y.H. Ji, J.J. Park, Development of severe plastic deformation by various asymmetric rolling processes, Mater. Sci. Eng., A, 499, 2009, 14-17.
8. A.B. Esbolat, E.A. Panin, A.S. Arbuz, A.B. Naizabekov, S.N. Lezhnev, A.S. Yerzhanov, I.I. Krupenkin, I.E. Volokitina, A.V. Volokitin, Development of Asymmetric Rolling as a Severe Plastic Deformation Method: A Review, J. Ultrafine Grained Nanostruct. Mater., 55, 2, 2022, 97-111.
9. A. Esbolat, E. Panin, A. Arbuz, D. Kuis, S. Lezhnev,I. Krupenkin, M. Erpalov, Concepts analysis of asymmetry factor implementation during rolling in relief rolls, J. Chem. Technol. Metall., 57, 6, 2022, 1243-1250.
10. W.J. Kim, J.B. Lee, W.Y. Kim, H.T. Jeong, H.G. Jeong, Microstructure and mechanical properties of Mg-Al-Zn alloy sheets severely deformed by asymmetrical rolling, Scr. Mater., 56, 4, 2007, 309-312.
11. L.L. Chang, J.H. Cho, S.B. Kang, Microstructure and mechanical properties of AM31 magnesium alloys processed by differential speed rolling, J. Mater. Process. Technol., 211, 9, 2011, 1527-1533.
12. W.J. Kim, Y.G. Lee, M.J. Lee, J.Y. Wang, Y.B. Park, Exceptionally high strength in Mg-3Al-1Zn alloy processed by high-ratio differential speed rolling, Scr. Mater., 65, 12, 2011, 1105-1108.
13. A. Pesin, D.O. Pustovoytov, Influence of Process Parameters on Distribution of Shear Strain through Sheet Thickness in Asymmetric Rolling, Key Eng. Mater., 622-623, 2014, 929-935.
14. J.N. Sun, C. Chen, S. Wang, G.N. Liu, H.G. Huang, Analysis of longitude profiled rolling process of Cu/Al cladded sheet and evaluation of outlet warpage, J. Iron Steel Res. Int., 29, 6, 2022, 973-982.
15. D. Rydz, B. Koczurkiewicz, G. Stradomski, T. Garstka, J. Wypart, The effect of the asymmetrical rolling process on structural changes in hot-rolled bimetal sheets, Arch. Metall. Mater., 64, 4, 2019, 1495-1501.
16. A.M. Pesin, D.O. Pustovoitov, O.D. Biryukova, The effect of speed asymmetry on the strain state in aluminium bimetals during accumulative rolling, IOP Conf. Ser.: Mater. Sci. Eng., 447, 1, 2018, 012066.
17. M.H. Vini, S. Daneshmand, Investigation of bonding properties of Al/Cu bimetallic laminates fabricated by the asymmetric roll bonding techniques, Adv. Comput. Des., 4, 1, 2019, 33-41.