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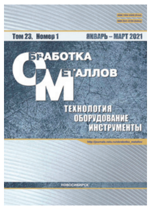

Invariant stress state parameters for forging upsetting of magnesium in the shell

Yuriy Loginov [1, 2, a,*], *Yuliya Zamaraeva* [1, 2, b]

[1] Ural Federal University named after the fi rst President of Russia B.N. Yeltsin, 19 Mira str., Ekaterinburg, 620002, Russian Federation
[2] M.N. Mikheev Institute of Metal Physics of the Ural Branch of the Russian Academy of Sciences, 18 S. Kovalevskaya str., Ekaterinburg, 620137, Russian Federation

[a] https://orcid.org/0000-0002-7222-2521, j.n.loginov@urfu.ru, [b] https://orcid.org/0000-0002-2620-7064, zamaraevajulia@yandex.ru

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ABSTRACT

Introduction. For pressure treatment of low-plastic metals, it is necessary to develop special techniques for increasing plasticity. In the cold state, an increase in plastic properties is possible due to an increase in the level of compressive stresses during deformation. In the processes of upsetting, this is achieved by using shells or clips of various types. At the same time, the configuration of the upsetting tool also matters. To create additional compressive stresses and increase the ductility of the metal, the working surface of the tool can be configured differently than with a normal free upsetting, where it is obviously larger than the contact surface area of the workpiece, so that metal broadening can occur. The stress state has a great influence on the plasticity of the processed material. This state is described by methods of tensor representation, but to assess the situation, it is customary to use invariants of tensors in one form or another, which eliminates the influence of coordinates on the results of the analysis. In the sections of deformable body mechanics dealing with the influence of the stress state on plasticity, the first, but sometimes other invariants of the stress tensor are used, the invariants themselves are transformed into the stress state indicator and the Lode coefficient. **The aim of the work:** mathematical evaluation of invariant parameters of the stress state of the magnesium upsetting process at room temperature, according to the results of which it is possible to obtain a positive result in real experiments. **Research methods:** finite element simulation using the DEFORM software module. **Results and discussion.** The theoretical justification of increasing the plasticity of the magnesium billet in the process of upsetting in the cage without its compression is carried out. An increase in the stress state index modulo 2...5 times is revealed, which contributes to an increase in the plasticity of the metal. At the same time, a zone with a Lode coefficient close to zero is identified. It is adjacent to the middle of the height of the workpiece at the point of contact with the cage and can be a dangerous cross-section from the position of crack formation.

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Introduction

The plastic properties of the metal should be considered during developing the manufacturing process of a metal's pressure shaping. Increasing plasticity in low-plastic metals requires developing special techniques. Basically, efforts are aimed at increasing the level of plastic properties by increasing the temperature. However, this approach does not always suit the developers of the technology since a number of metals begin to oxidize from the surface when the temperature rises, or there occurs the process of gas saturation of the bulk metal. This is especially true for metals such as titanium [1] and magnesium [2]. Therefore, there may also be an approach in which the processing is carried out in a cold state and the plasticity increases due to an increase in the level of compressive stresses [3] during the deformation process.

*** Corresponding author**
Zamaraeva Yuliya V., Junior researcher
M.N. Mikheev Institute of Metal Physics
of the Ural Branch of the Russian Academy of Sciences,
18 S. Kovalevskaya str.,
620137, Ekaterinburg, Russian Federation
Tel.: +7-950-200-56-79, **e-mail:** zamaraevajulia@yandex.ru

In the process of upset forging, this is achieved by using shells or clips of various types [4-6]. Besides, the configuration of the upsetting tool also matters. For example, with a normal free upsetting, the tool has a working surface, the area of which is obviously larger than the area of the contact surface of the billet, so that the processed metal broadening can occur. Here, the deformation process is hindered only by friction stresses that create additional radial and tangential stresses that increase the hydrostatic pressure. However, the working surface can be configured differently, which creates additional compression stresses and increases the plasticity of the metal. The combination of the billet and the shell creates a bimetal configuration; this requires using complex solutions to boundary value problems, which have increasingly been solved by the finite element method [7].

The stress state has a great influence on the plasticity of the processed material. This state is described by tensor representation methods, but it is customary to use tensor invariants in one form or another to assess the situation, which eliminates the influence of coordinates on the analysis results. In the sections of deformable body mechanics concerning the influence of the stress state on plasticity, the first stress tensor is used, as well as other invariants [8]; the invariants themselves are transformed into the stress state indicator [9, 10] and the Lode coefficient [11, 12].

The use of the shell in earlier studies of the upsetting process was associated with the use of a working tool impact scheme simultaneously on the end of the billet and the end of the shell. Another, newer scheme, according to which the tool acts only on the end of the billet, was tested only experimentally [13]; the scheme enabled obtaining a magnesium billet without destruction and cracks. The invariants of the stress tensor are known to be responsible for increasing the plasticity of the metal in the processes of plastic deformation.

The purpose of the work is to mathematically evaluate the invariant parameters of the stress state of the shelled magnesium upsetting process when the tool is applied only to the end of the billet.

Research Methodology

The experimental part

The physical experiments were performed on the forging and pressing equipment of the Mikheev Institute of Metal Physics of the Ural Branch of the Russian Academy of Sciences, their detailed description is given in a number of publications [13–15]. To avoid self-citation, only the essence of the process is described below. Magnesium of the Mg90 grade according to GOST 804-93 was used as the material of the billet. The following dimensions were taken in the experiment: a billet in the form of a cylinder made of magnesium with a diameter of 21.8 mm and a height of 25 mm, a copper shell has an outer diameter of 48 mm and a height of 29.5 mm, the inner diameter of the shell is equal to the diameter of the magnesium billet. The upsetting was carried out with 25 mm in diameter punches. The absolute compression was 5.9 mm. The diameter of the shell increased to 49.8...50.2 mm at the contact with the strikers and to 52.9...53.2 mm in the middle part. In experiments according to this scheme, there was no destruction of the billet metal revealed, while with a normal upsetting, the billet was destroyed.

Calculation

This paper deals with a computational experiment, i.e. an assessment of the stress-strain state of the deformation process, whose implementation allowed imposing a certain level of deformation to magnesium billets in the cold state. This estimation was performed by the finite element method using the DEFORM software module [16]. The task is to determine the conditions for the absence of cracking, i.e. the destruction of the metal. Further, we will use the basics of the destruction theory expounded, for example, in the book [17]. Destruction occurs when the maximum degree of shear deformation Λ_p is exceeded, which, in turn, depends on the stress state index σ/T and the Lode coefficient μ_σ; here σ is the mean (hydrostatic) stress, T is the intensity of tangential stresses associated with the stress intensity σ_i the ratio

$$T = \frac{\sigma_i}{\sqrt{3}}. \quad (1)$$

The indicator μ_σ is determined by the ratio

$$\mu_\sigma = 2\frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3} - 1, \quad (2)$$

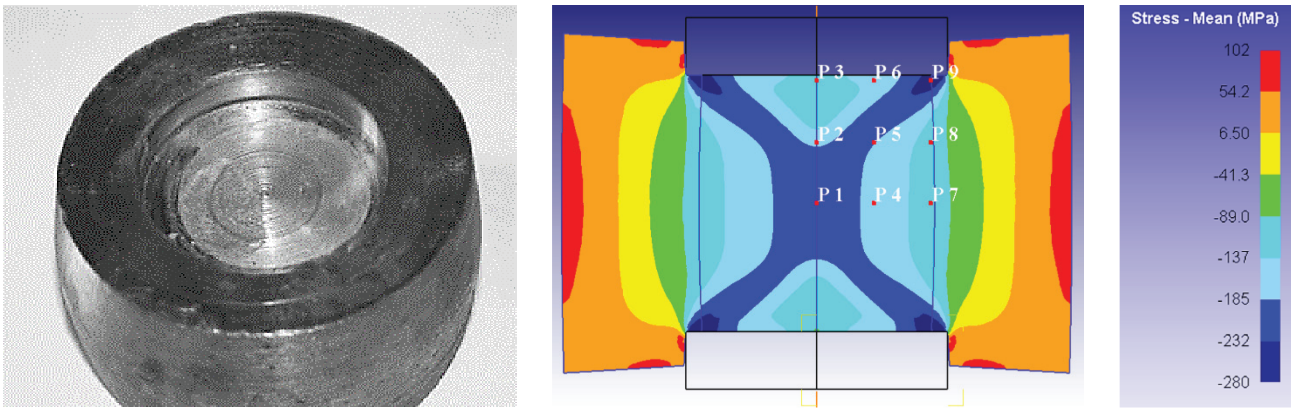
where σ_i (i = 1, 2, 3) are the main normal voltages; the voltages are ranked according to the rule $\sigma_1 \geq \sigma_2 \geq \sigma_3$, i.e. the numbering begins with the maximum voltage and ends with the minimum.

The DEFORM system provides for the possibility of calculating the maximum (first) and minimum (third) main normal voltages, but the second main voltage is not calculated. Therefore, it was determined specifically by calculating the formula

$$\sigma_2 = 3\sigma - (\sigma_1 + \sigma_3). \quad (3)$$

Another problem is the absence in the list of variables calculated in the DEFORM system: the stress state index σ/T and the Lode coefficient μ_σ; they were calculated specifically and brought to a tabular form.

Application of a shell and changing the configuration of the tool surface was proposed in the scheme of cold upsetting of a magnesium billet to achieve higher plasticity [18]. The difference from the usual schemes of using the shell is that the shell is larger in height than the billet, with the punch not affecting the assembly as a whole, only the billet (Fig. 1, *a*). Copper is used as the shell material, its properties are described using reference materials.



a *b*

Fig. 1. Photo of the assembly (*a*) and calculation model of the process (*b*) upsetting of a magnesium billet in a shell with an estimation of mean stresses (stress mean)

The problem statement included a description of physical and plastic properties based on reference data and the setting of boundary conditions in displacements. We used the model of an isotropic medium with hardening, which is described in the article [19].

Interactions on the contact surfaces are established: billet-strikers, billet-shell. At the contact with the tool, the law of friction is set according to the Coulomb with a coefficient of friction being 0.1 since the upsetting was carried out with lubrication. There is no lubrication at the boundary between the workpiece and the shell, and since both materials – copper and magnesium - have increased adhesive properties, the coefficient of friction on this surface was assumed to be equal to 0.5.

Results and discussion

The parameter σ/T is not included in the number of parameters defined by the DEFORM software module, just like the parameter T. For additional calculations, we had to assign control points P1,..., P9, setting the relative coordinates *z/h* = 0; 0.5; 1; *r/R* = 0; 0.5; 1. Here, *z* and *r* are the current coordinates along the radius and vertical axis; *h* and *R* are half the height and radius of the workpiece. At these points, the values of the stress mean parameter, which corresponds to the concept of average stress (Fig. 1, *b*), and the stress effective parameter, which corresponds to the concept of stress intensity σ_{and} (Fig. 2), are estimated.

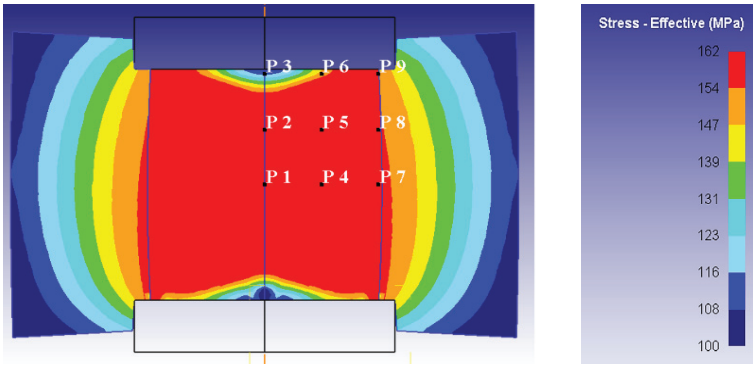


Fig. 2. The distribution of stress intensity

Naturally, stretching medium stresses up to +102 MPa are preferably applied in the shell (Fig. 1, *b*), their presence creates a danger of destruction, which is why such a plastic material as copper is used here. The distribution of average stresses in a magnesium billet resembles a picture of a "transverse crack", known from the theory of forging. Here, the zone of increased (modulo) values is stretched along the diagonals of the billet longitudinal section with a voltage of 280 MPa. With conventional forging, it is along the lines of the "transverse crack" that a split of the billet is possible. In this case, the high (modulo) values of the average normal stress give hope for an increase in the level of plasticity, which should prevent destruction.

A different picture is observed for the distribution of stress intensity (Fig. 2): they decrease from the center to the periphery, i.e. in the direction of the free surface. The stress gradient is especially large at the interface between the billet and the shell, which is explained by the difference in the mechanical properties of the materials. In the zones of difficult deformation adjacent to the centers of the ends of the punches, the stress intensity decreases, which is due to the lack of metal hardening in this area.

The calculated data on the stress state indicator at the control points P1-P9 are presented in Table 1.

Since the plasticity of metals decreases with an increase in the index σ/T, it follows from the table that the hazardous zones are adjacent to the points with coordinates *z/h* = 0 and *r/R* = 1. At the same time, the values of σ/T have negative values everywhere, i.e. compression stresses prevail. The table shows that the indicator σ/T can vary at this stage of processing within –1.21...–3.02. The highest modulo values at the level of –3.02 are characteristic of the peripheral points adjacent to the contact surface. In this case, the unfavorable (the lowest modulo) values are located in the area of the lateral surface convexity. The results obtained can be compared to the results of a cylindrical billet upsetting by smooth strikers without friction. In this case, the stress state indicator for the entire volume of the billet is known to be the same and equal

Table 1

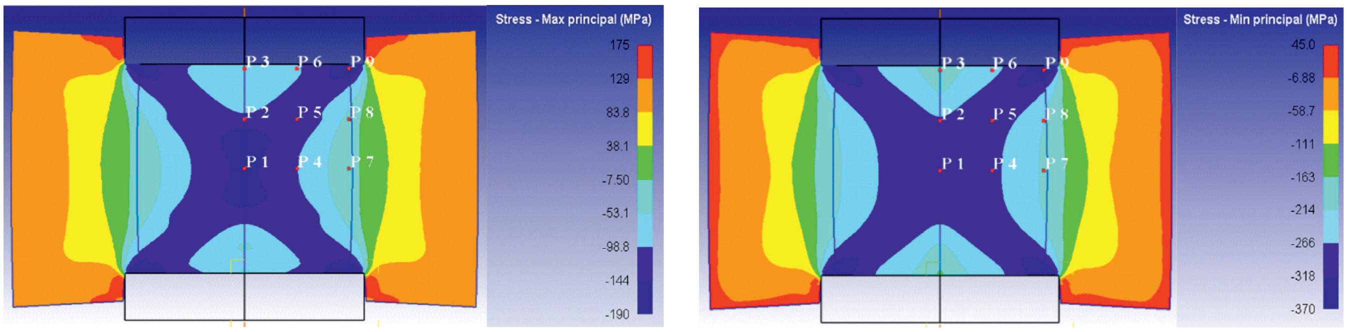
Value of σ/T at P1 - P9 control points

z/h	*r/R*		
	0	0.5	1
1	–1.99	–1.75	–3.02
0.5	–1.86	–2.01	–1.24
0	–2,15	–1,83	–1,21

to - 0.58. Comparing this value with the results shown in the table shows that there was an increase in the indicator absolute values by 2 to 5 times. That is why the plasticity of the metal in the experiments increased and it turned out to be sufficient for the operation of upsetting without destruction.

The results obtained can also be compared with the variant of friction upsetting of a cylindrical billet in a shell while locating the entire assembly on the strikers' contact surface. This variant leads to a greater amount of metal displacement in the zone of the convexity emergence on the lateral surface [20] and the shell clearance from the billet. In the absence of a pad and the formation of a convex surface, the average normal stresses in this zone can change from the compressive to the tensile ones. The lateral surface of the billet with insufficiently high plasticity can be destroyed. Therefore, the shell should not be exposed to axial stresses.

The distribution of the maximum and minimum main stresses is shown in Fig. 3.



a *b*

Fig. 3. Distribution of the maximum (*a*) and minimum (*b*) principal stress

It can be seen that the scheme of the transverse crack is repeated for the main stresses. Calculating the second main stress enabled calculating the coefficient μ_σ. The results of calculations of the main normal stresses are shown in Table 2.

Table 2

Principal normal stresses (MPa) and Lode coefficient σ_1 / σ_2 / σ_3 / μ_σ at relative coordinates

z/h	*r/R*		
	0	0.5	1
1	–92/–92/–205/0.98	–95/–106/–248/0.86	–190/–262/–370/0.2
0.5	–119/–118/–279/0.98	–118/–153/–293/0.60	–39/–90/–219/0.43
0	–148/–148/–310/1.00	–104/–138/–280/0.61	–23/–111/–208/0.05

All the main stresses are negative values, i.e. they are compression stresses. The danger of possible destruction is represented by control points with the lowest modulo of the main stresses. These include the point P7 with coordinates *z/h* = 0; *r/R* = 1, here $\sigma_1 = -23$ MPa. At the same point, the Lode coefficient reaches values close to zero, in contrast to the points located on the axis of the billet, where this coefficient is close to one. At a zero value of the Lode coefficient, the plasticity is the lowest, as indicated by a number of works [21, 22]. Therefore, the specified area can be considered a dangerous cross-section in terms of crack formation.

As can be seen from all the above illustrations and the results of a real experiment, in the studied upsetting method, there is no shell clearance from the workpiece. During the entire upsetting process, radial compression stresses act on the lateral surface of the billet increasing the plasticity of the metal and allowing the deformation to be carried out without destruction.

Conclusion

Calculations of the stress-strain state show that the magnesium upsetting in the shell with the pressing tool is acting only to the end of the billet should lead to an increase in the plasticity of the metal, which was previously shown experimentally.

An increase in the stress state index modulo by 2...5 times was revealed when comparing it with the stress state indicator for normal upsetting. Additionally, a zone with a Lode coefficient close to zero was identified. It is adjacent to the middle of the height of the billet at the point of contact with the shell and can be a dangerous cross-section in terms of crack formation.

References

1. Kudiiarov V.N., Lider A.M., Harchenko S.Y. Hydrogen accumulation in technically pure titanium alloy at saturation from gas atmosphere. *Advanced Materials Research*, 2014, vol. 880, pp. 68–73. DOI: 10.4028/www.scientific.net/AMR.880.68.

2. Esmaily M., Svensson J.E., Fajardo S., Birbilis N., Frankel G.S., Virtanen S., Arrabal R., Thomas S., Johansson L.G. Fundamentals and advances in magnesium alloy corrosion. *Progress in Materials Science*, 2017, vol. 89, pp. 92–193. DOI: 10.1016/j.pmatsci.2017.04.011.

3. Proust G. Processing magnesium at room temperature. *Science*, 2019, vol. 364 (6448), pp. 30–31. DOI: 10.1126/science.aax9732.

4. Chang L.L., Wang Y.N., Zhao X., Huang J.C. Microstructure and mechanical properties in an AZ31 magnesium alloy sheet fabricated by asymmetric hot extrusion. *Materials Science and Engineering: A*, 2008, vol. 496, iss. 1–2, pp. 512–516. DOI: 10.1016/j.msea.2008.06.015.

5. Loginov Yu.N., Kamenetsky B.I., Zamaraeva Yu.V. Mezhsloinoe vzaimodeistvie pri osadke bimetallicheskoi zagotovki [Interlayed interaction in the upsetting of the bimetallic billets]. *Kuznechno-shtampovochnoe proizvodstvo. Obrabotka materialov davleniem = Forging and Stamping Production. Material Working by Pressure*, 2019, no. 7, pp. 41–45.

6. Pan F., Wang Q., Jiang B., He J., Chai Y., Xu J. An effective approach called the composite extrusion to improve the mechanical properties of AZ31 magnesium alloy sheets. *Materials Science and Engineering: A*, 2016, vol. 655, pp. 339–345. DOI: 10.1016/j.msea.2015.12.098.

7. Khanawapee U., Butdee S. A study of barreling and DEFORM 3D simulation in cold upsetting of bi-material. *Materials Today: Proceedings*, 2020, vol. 26, pt. 2, pp. 1262–1270. DOI: 10.1016/j.matpr.2020.02.252.

8. Malcher L., Mamiya E.N. An improved damage evolution law based on continuum damage mechanics and its dependence on both stress triaxiality and the third invariant. *International Journal of Plasticity*, 2014, vol. 56, pp. 232–261. DOI: 10.1016/j.ijplas.2014.01.002.

9. Yoon J.W., Lou Y., Yoon J., Glazoff M.V. Asymmetric yield function based on the stress invariants for pressure sensitive metals. *International Journal of Plasticity*, 2014, vol. 56, pp. 184–202. DOI: 10.1016/j.ijplas.2013.11.008.

10. Driemeier L., Micheli G., Alves M., Brünig M. Experiments on stress-triaxiality dependence of material behavior of aluminum alloys. *Mechanics of Materials*, 2010, vol. 42, iss. 2, pp. 207–217. DOI: 10.1016/j.mechmat.2009.11.012.

11. Xiao X., Mu Z., Pan H., Lou Y. Effect of the lode parameter in predicting shear cracking of 2024-t351 aluminum alloy Taylor rods. *International Journal of Impact Engineering*, 2018, vol. 120, pp. 185–201. DOI: 10.1016/j.ijimpeng.2018.06.008.

12. Mirone G., Corallo D. A local viewpoint for evaluating the influence of stress triaxiality and lode angle on ductile failure and hardening. *International Journal of Plasticity*, 2010, vol. 26, iss. 3, pp. 348–371. DOI: 10.1016/j.ijplas.2009.07.006.

13. Kamenetsky B.I., Loginov Yu.N., Volkov A.Yu. Metody i ustroistva dlya povysheniya plastichnosti khrupkikh materialov pri kholodnoi osadke s bokovym podporom [Methods and apparatus for increase of brittle materials plasticity under cold upsetting with lateral support]. *Zagotovitel'nye proizvodstva v mashinostroenii = Blanking productions in mechanical engineering*, 2013, no. 9, pp. 15–22.

14. Volkov A.Yu., Antonova O.V., Kamenetskii B.I., Klyukin I.V., Komkova D.A., Antonov B.D. Poluchenie, struktura, tekstura i mekhanicheskie svoistva sil'no deformirovannykh obraztsov magniya [Production, structure,

texture, and mechanical properties of severely deformed magnesium]. *Fizika metallov i metallovedenie = Physics of Metals and Metallography*, 2016, vol. 117, iss. 5, pp. 518–528. DOI: 10.1134/S0031918X16050161. (In Russian).

15. Kamenetsky B.I., Loginov Yu.N., Kruglikov N.A. Vliyanie uslovii bokovogo podpora na plastichnost' magniya pri kholodnoi osadke [The effect of lateral back pressure conditions on magnesium plasticity during cold upsetting]. *Tekhnologiya legkikh splavov = Technology of light alloys*, 2012, no. 1, pp. 86-92.

16. Design Environment for forming: website. 2021. Available at: http://www.DEFORM.com (accessed 08.02.2021).

17. Kolmogorov V.L. *Mekhanika obrabotki metallov davleniem* [Mechanics of metal processing by pressure]. Ekaterinburg, Ural State Technical University Publ., 2001. 834 p.

18. Loginov Yu.N., Zamaraeva Yu.V., Kamenetskiy B.I. Osadka tsilindricheskoi magnievoi zagotovki v mednoi obolochke bez ee obzhatiya [Upsetting of cylinder magnesium blanks in copper casing without compression]. *Tsvetnye metally*, 2020, no. 4, pp. 77–82. DOI: 10.17580/tsm.2020.04.09. (In Russian).

19. Komkova D.A., Volkov A.Yu. Struktura i tekstura magniya posle nizkotemperaturnoi megaplasticheskoi deformatsii [Magnesium structure and texture after the low-temperature megaplastic deformation]. *Vektor nauki Tol'yattinskogo gosudarstvennogo universiteta = Science Vector of Togliatti State University*, 2017, no. 3 (41), pp. 70–75.

20. Narayanasamy R., Pandey K.S. Phenomenon of barrelling in aluminium solid cylinders during cold upset-forming. *Journal of Materials Processing Technology*, 1997, vol. 70, iss. 1–3, pp. 17–21. DOI: 10.1016/S0924-0136(97)00035-6.

21. Ganjiani M. A damage model for predicting ductile fracture with considering the dependency on stress triaxiality and Lode angle. *European Journal of Mechanics – A/Solids*, 2020, vol. 84, p. 104048. DOI: 10.1016/j.euromechsol.2020.104048.

22. Smirnov S.V., Vichuzhanin D.I., Nesterenko A.V. Kompleks ispytanii dlya issledovaniya vliyaniya napryazhennogo sostoyaniya na predel'nuyu plastichnost' metalla pri povyshennoi temperature [A set of tests for studying the effect of the stress state on ultimate metal plasticity at high temperature]. *Vestnik PNIPU. Mekhanika = PNRPU Mechanics Bulletin*, 2015, vol. 3, pp. 146–164. DOI: 10.15593/perm.mech/2015.3.11.

Conflicts of Interest

The authors declare no conflict of interest.