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Evaluation of the Stress–Strain State of the Wire during the Developed Thermomechanical Processing

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This work considers the results of modelling the stress–strain state of the wire in the implementation of a new thermomechanical processing technology, which is a combined process of drawing and continuous cooling in a special chamber using liquid nitrogen. The absence of heating to ambient temperature causes an increase in the level of equivalent stress by 5–10%. An increase in the deformation rate causes a decrease in the stress level due to an increase in deformation heating. The development of cross-sectional strain occurs unevenly, the surface receives a higher level of strain. As the number of passes increases, this difference increases due to the cumulative nature of the equivalent strain.

Key words: modelling, steel, wire, drawing, cryogenic cooling, stress–strain state.

У роботі розглянуто результати моделювання напружено-деформованого стану дроту під час реалізації нової технології термомеханічного оброблення, що являє собою поєднаний процес волочіння та безперервного охолодження у спеціяльній камері з використанням рідкого азоту. Відсутність нагрівання до температури навколишнього середовища приводить до збільшення рівня еквівалентних напружень на 5–10%. Збільшення швидкости деформації приводить до пониження рівня напружень за рахунок збільшення деформаційного нагрівання. Розвиток деформації по-

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перечного перерізу відбувається нерівномірно, поверхня отримує більш високий рівень деформації. Зі збільшенням числа проходів ця ріжниця зростає через кумулятивний характер еквівалентної деформації.

Ключові слова: моделювання, криця, дріт, волочіння, кріогенне охолодження, напружено-деформований стан.

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1. INTRODUCTION

As the basis for creating a variety of materials, metals have unique properties that directly depend on their internal structure. This dependence is key factor to understanding how to create materials with specified characteristics.

Thanks to the development of technology, it is possible to create materials with unique properties that meet the increasingly complex requirements of modern industry [1–5]. One of the most important ways to increase the strength and wear resistance of metals is to reduce the grain size in their structure. The smaller the grain, the more difficult it is for dislocations to move, which increases the deformation resistance. Therefore, reducing the grain size makes the material more resistant to deformation and destruction; they withstand repeated loads better, and resist corrosion better, which prolongs their service life in aggressive environments [6–8].

Methods of severe plastic deformation (SPD) make it possible to obtain ultrafine-grained and nanomaterials with unique properties [9–15]. Such SPD methods, as high-speed stamping, extrusion and rolling, have a number of advantages, allowing you to obtain materials with unique properties and characteristics. However, along with this, they also have their drawbacks, which must be taken into account when applying them.

One of the key disadvantages is the discreteness of the processes. Unlike traditional processing methods, where deformation occurs continuously, severe deformation methods involve a series of individual pulses or cycles [16–18]. This can lead to an uneven distribution of strain over the workpiece volume, as well as to the occurrence of microcracks and other defects. The heterogeneity of the microstructure may also be related to the peculiarities of the deformation process. Crystal lattice defects such as dislocations, vacancies, and interstitial atoms can form in areas of intense deformation. These defects, in turn, can affect the strength, ductility and fatigue strength of the material.

Another significant disadvantage is the complexity and wear of the tool. The tool used for severe plastic deformation must be made of high-strength and wear-resistant materials capable of withstanding high loads and temperatures. This significantly complicates the manufacturing process and increases its cost. In addition, the tool is subject to intense wear and tear, requiring regular replacement or restoration.

In general, methods of severe plastic deformation are a powerful tool for obtaining materials with unique properties. However, it is necessary to carefully analyse all their advantages and disadvantages, as well as optimize the technological process in order to minimize the negative impact of these disadvantages.

Cryogenic cooling is another direction that grinds the microstructure of metal [19–21]. This is an effective method for producing materials with a fine-grained structure and improved mechanical properties. The essence of the method is to cool the material to extremely low temperatures, usually to −196°C (liquid nitrogen temperature), which leads to a significant slowdown in diffusion processes in the metal.

During cryogenic cooling, metal atoms become less mobile, which prevents their rearrangement and the formation of large grains. As a result, the structure of the material becomes more fine-grained, which leads to an increase in its strength, hardness and wear resistance.

The use of cryogenic cooling in combination with thermomechanical treatment makes it possible to achieve results, which are even more impressive. Thermomechanical processing involves a combination of deformation and thermal action, which allows you to control the structure and properties of the material at the micro level. At the same time, cryogenic cooling after thermomechanical treatment makes it possible to ‘freeze’ the structure obtained as a result of deformation. This leads to the preservation of a fine-grained structure and an increase in the strength of the material.

In the case of wire, cryogenic cooling can be used to increase its strength, hardness and wear resistance, which makes it more resistant to bending, stretching and wear. This is especially important in cases where the wire is used in conditions of high loads and aggressive environments. Therefore, we propose to carry out cryogenic cooling of the wire immediately after heating it in the fibre in order to ‘freeze’ the structure obtained as a result of deformation.

It is important to note that cryogenic cooling is a technology that requires special equipment and knowledge. Cryogenic cooling is based on cooling the material to ultra-low temperatures (below −150°C), which leads to a change in its microstructure and, as a result, to a change in physical and mechanical properties. Improper use of such technology can lead to unpredictable consequences: from damage to the material to equipment failure. Therefore, before using cryogenic cooling, it is necessary to study carefully the characteristics of the material and the rules of its processing.

At the initial stage, it is recommended to simulate a new thermomechanical treatment in a special ‘Deform’ software package. It allows visualizing the cooling process and analysing possible risks and changes in the structure of the material. This will minimize the risks and get the most out of cryogenic cooling.

The 'Deform' program uses the finite element method to simulate complex physical processes, including heat transfer, deformation, and phase change. It allows taking into account the influence of various parameters such as temperature, pressure, cooling rate and holding time [22–25].

Therefore, the novelty of this article is the modelling of a new thermomechanical treatment of steel wire to determine the optimal cryogenic cooling modes, which will maximize the efficiency of this technology.

2. EXPERIMENTAL

The developed technology of thermomechanical wire processing is a combined process of wire drawing and continuous cooling in a special chamber using liquid nitrogen. This chamber is located in the rolling line directly behind the drawing machine. When the drawing machine reaches the operating speed, the chamber is filled with liquid nitrogen. The degree of compression is 5–7%. This means that in the first pass the steel is deformed from 6 mm to 5.6 mm, in the second pass—from 5.6 mm to 5.3 mm, in the third—from 5.3 mm to 5 mm. In addition, it was decided to consider the possibility of drawing thicker wire with a diameter of 9 mm. Here, the workpiece was stretched to 8.2 mm, from 8.2 mm to 7.5 mm in the second pass and from 7.5 mm to 7 mm in the third pass.

The simulation was carried out at two deformation speeds: 500 mm/s and 1000 mm/s. Accordingly, it was assumed that any wire section is in liquid nitrogen for a certain amount of time: 1 s at a speed of 500 mm/s and 0.5 s at a speed of 1000 mm/s. As a result, the workpiece after such a short-term treatment with liquid nitrogen will have a significant temperature gradient across the cross section, which will lead to an uneven distribution of mechanical properties. In the first variant, after each treatment with liquid nitrogen, the workpiece was heated to 20 °C in air. In the second variant, this heating was not carried out.

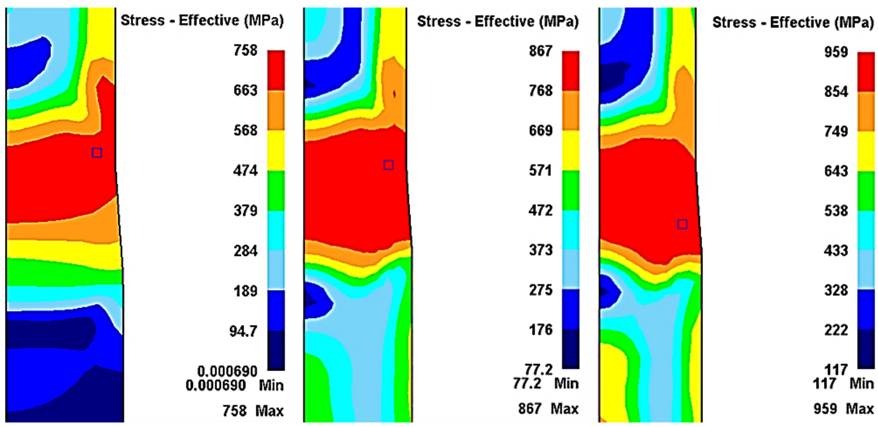
The assessment of the stress–strain state during the deformation process is a key task of theoretical research. The analysis of the strain state allows assessing the overall level of metal processing at any point of the workpiece. Stress analysis makes it possible to assess the stresses that arise, to determine the zones where the tensile strength is exceeded (these zones are places of potential defect formation).

When studying the strain state during drawing, an indicator of the intensity of strain (equivalent strain) is usually considered. This reflects the overall level of metal processing. The study of the stress state during drawing involves determining the conditions under which the resulting level of equivalent stresses will be less than the tensile strength of the material. Otherwise, it will be inevitable that the wire will break in the area between the drawing die and the pulling mechanism.

3. RESULTS AND DISCUSSION

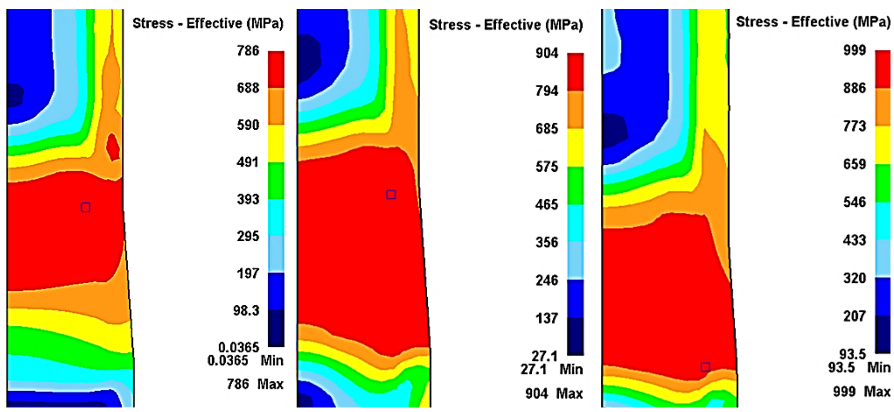
Figures 1, 2 show pictures of equivalent stresses for drawing models of both workpieces at 500 mm/s with the workpiece heated to 20 °C.

Using the local scale display, it is possible to see the minimum and maximum of the parameter at the selected calculation step. Since in these models the properties of the material at each stage of drawing correspond well to the nomogram of the tensile strength of AISI-316 steel, it was decided to compare the obtained values of the maximum



a *b* *c*

Fig. 1. Equivalent stresses in a model of drawing from 6 mm to 5 mm at a speed of 500 mm/s while heating the workpiece to 20°C after each pass.



a *b* *c*

Fig. 2. Equivalent stresses in the drawing model from 9 mm to 7 mm at 500 mm/s with the workpiece heated to 20°C after each pass.

TABLE 1. Stress state parameters in models with workpiece heating up to 20°C.

Pass No.	D_0, mm	D_1, mm	TS_0, MPa	TS_1, MPa	$\sigma_{EQV\ 500}$, MPa	$\sigma_{EQV\ 1000}$, MPa
Drawing a workpiece with a diameter of 6 mm						
1	6	5.6	862	1038	758	744
2	5.6	5.3	1038	1156	867	853
3	5.3	5	1156	1284	959	946
Drawing a workpiece with a diameter of 9 mm						
Pass No.	D_0, mm	D_1, mm	TS_0, MPa	TS_1, MPa	$\sigma_{EQV\ 500}$, MPa	$\sigma_{EQV\ 1000}$, MPa
1	9	8.2	862	1080	786	772
2	8.2	7.5	1080	1284	904	886
3	7.5	7	1284	1420	999	974

equivalent stresses with the values of the tensile strength. Table 1 shows the summary values of these parameters from models with both drawing speeds.

As can be seen in Table 1, in all passes for each wire size, the value of equivalent stresses does not exceed the lower limit of the tensile strength. This allows concluding that the deformation process is stable without the danger of wire rupture. This approach to stress assessment in the presence of a strength limit nomogram corresponding to the specified conditions is an effective way to predict the possible formation of defects, the modelling of which seems to be quite a difficult task in terms of the accuracy of the results obtained. It can be seen from the data obtained that an increase in the deformation speed, leading to an increase in the level of deformation heating, causes a decrease in the level of equivalent stresses. At the same time, it should be noted that, despite the twofold increase in the drawing speed, the decrease in the stress level is insignificant. In all cases, the stress values were decreased by about 1–3%.

A comparison of models without preheating the workpiece is shown in Table 2. As shown by the study of temperature fields, the absence of heating to ambient temperature leads to an increase in the temperature gradient in the workpiece section, which ultimately causes an increase in the level of equivalent stresses by about 5–10%. At the same time, there is also no crossing of the lower limit of the tensile strength.

Analysing the strain state, it should be noted that any parameter of the strain state is accumulative, and their values depend on the geometric parameters. Accordingly, the point estimation method previously used to estimate temperature is suitable for their assessment. Figure 3 shows graphs of the accumulation of equivalent strain for both thicknesses of workpieces. Measurements were carried out on the

TABLE 2. Stress state parameters in models without preheating the workpiece.

Drawing a workpiece with a diameter of 6 mm						
Pass No.	D_0, mm	D_1, mm	TS_0, MPa	TS_1, MPa	$\sigma_{EQV\ 500}$, MPa	$\sigma_{EQV\ 1000}$, MPa
1	6	5.6	862	1038	758	744
2	5.6	5.3	1038	1156	**956**	**932**
3	5.3	5	1156	1284	**1018**	**1003**
Drawing a workpiece with a diameter of 9 mm						
Pass No.	D_0, mm	D_1, mm	TS_0, MPa	TS_1, MPa	$\sigma_{EQV\ 500}$, MPa	$\sigma_{EQV\ 1000}$, MPa
1	9	8.2	862	1080	786	772
2	8.2	7.5	1080	1284	**1010**	**944**
3	7.5	7	1284	1420	**1044**	**1022**

surface (point *1*) and on the axis of the workpiece (point *2*). Both graphs have an identical appearance, consisting of three stages that characterize the drawing stages. The horizontal sections correspond to the cooling stages in liquid nitrogen.

Taking into account the fact that sufficiently high drawing speeds are used in modelling, planes with specified points pass through the deformation zone almost instantly. This leads to the fact that these sections of the graphs have a vertical appearance. It should be noted that the overall level of strain is higher when using a 9 mm thick blank. However, this is a consequence of the fact that when deformed, it receives a higher level of total compression (39.5% *versus* 30.55% for a workpiece with a thickness of 6 mm).

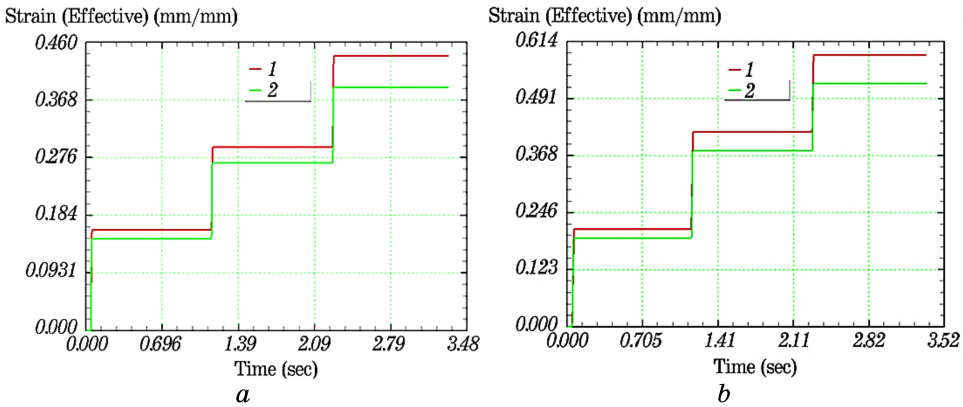


Fig. 3. Graphs of equivalent strain: drawing model from 6 mm to 5 m (*a*); drawing model from 9 mm to 7 mm (*b*).

4. CONCLUSION

The paper considers the results of modelling the stress–strain state of the wire in the implementation of a new thermomechanical processing technology, which is a combined process of drawing and continuous cooling in a special chamber using liquid nitrogen. A comparison of the values in models with and without workpiece heating showed that the absence of heating to room temperature causes an increase in the level of equivalent stresses by about 5–10%. At the same time, in both models, an increase in the deformation speed causes a decrease in the stress level due to an increase in deformation heating. The development of cross-sectional strain occurs unevenly, the surface receives a higher level of strain. In both models, an increase in the difference between the levels of strain on the surface and in the centre was recorded with an increase in the number of passes, which is explained by the fact that equivalent strain is a parameter of a cumulative (accumulated) nature.

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REFERENCES

1. I. E. Volokitina, A. V. Volokitin, and E. A. Panin, *Prog. Phys. Met.*, **23**, No. 4: 684 (2022).
2. V. V. Chigirinsky and I. E. Volokitina, *Metallofiz. Noveishie Tekhnol.*, **46**, No. 4: 343 (2024).
3. V. V. Chigirinsky, Y. S. Kresanov, and I. E. Volokitina, *Metallofiz. Noveishie Tekhnol.*, **45**, No. 4: 467 (2023).
4. I. E. Volokitina, A. V. Volokitin, M. A. Latypova, V. V. Chigirinsky, and A. S. Kolesnikov, *Prog. Phys. Met.*, **24**, No. 1: 132 (2023).
5. A. Bychkov and A. Kolesnikov, *Metallogr. Microstruct. Anal.*, **12**: 564 (2023).
6. I. E. Volokitina, *Prog. Phys. Met.*, **24**, No. 3: 593 (2023).
7. B. Sapargaliyeva, A. Agabekova, G. Ulyeva, A. Yerzhanov, and P. Kozlov, *Case Studies in Construction Materials*, **18**: e02162 (2023).
8. E. Panin, T. Fedorova, D. Lawrinuk, A. Kolesnikov, A. Yerzhanov, Z. Gelmanova, and Y. Liseitsev, *Case Studies in Construction Materials*, **19**: e02609 (2023).
9. N. Zhangabay, I. Baidilla, A. Tagybayev, Y. Anarbayev, and P. Kozlov, *Case Studies in Construction Materials*, **18**: e02161 (2023).
10. A. Volokitin, I. Volokitina, and E. Panin, *Metallogr. Microstruct. Anal.*, **11**: 673 (2022).
11. I. Volokitina, A. Volokitin, and D. Kuis, *J. Chem. Technol. Metall.*, **56**: 643 (2021).
12. I. Volokitina, A. Volokitin, A. Denissova, T. Fedorova, D. Lawrinuk, A. Kolesnikov, A. Yerzhanov, Y. Kuatbay, and Yu. Liseitsev, *Case Studies in Construction Materials*, **19**: e02346 (2023).
13. V. Chigirinsky and I. Volokitina, *Engineering Solid Mechanics*, **12**, No. 2: 113

(2024).
14. A. Nurumgaliyev, T. Zhuniskaliyev, V. Shevko, and G. Yerekeyeva, *Sci. Rep.*, **14**, No. 1: 7456 (2024).
15. A. Paradis, P. Terriault, and V. Brailovski, *Comput. Mater. Sci.*, **47**: 373 (2009).
16. G. Kurapov, E. Orlova, and A. Turdaliev, *J. Chem. Technol. Metall.*, **51**, No. 4: 451 (2016).
17. I. E. Volokitina and A. V. Volokitin, *Metallurg.*, **67**: 232 (2023).
18. D. A. Sinitsin, A. E. M. M. Elrefaei, A. O. Glazachev, E. I. Kayumova, and I. V. Nedoseko, *Construction Materials and Products*, **6**, No. 6: 2 (2023).
19. I. E. Volokitina, *Met. Sci. Heat Treat.*, **63**: 163 (2021).
20. W. H. Huang, C. Y. Yu, P. W. Kao, and C. P. Chang, *Mater. Sci. Eng., A*, **356**: 321 (2004).
21. M. Murugesan, D. Won, and J. Johnson, *Materials*, **12**: 609 (2019).
22. P. J. Arrazola, A. Garay, L. M. Iriarte, M. Armendia, S. Marya, and F. Le Maitre, *J. Mater. Process. Technol.*, **209**: 2223 (2009).
23. M. Dhananchezian and M.P. Kumar, *Cryogenics*, **51**: 34 (2011).
24. K. A. Venugopal, S. Paul, and A. B. Chattopadhyay, *Cryogenics*, **47**: 12 (2007).
25. R. Choudhary, H. Garg, M. Prasad, and D. Kumar, *Mater. Today: Proc.*, **4**, No. 2: 1158 (2017).