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Study of the Stress State in a Wire During Deformation Using a New Combined Technology

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In this article, the influence of a new combined-processing technology of copper wire on the stress state is investigated. This technology consists in deforming the wire in a rotating equal-channel step matrix and subsequent drawing. Deformation modelling is carried out at ambient temperature. To assess the effect of the workpiece twisting degree on the value of average hydrostatic pressure, the matrix-rotation speed is varied within 6, 18, and 30 rpm; the distance between the two deforming tools also is varied within 100, 200, and 300 mm. The simulation results reveal an inverse dependence of the intensity of compressive stresses on the matrix-rotation speed and a direct dependence on the gap magnitude between the deforming tools. Thus, with an increase in the matrix-rotation speed, the level of compressive stresses in all models is decreased by 1.5–2 times, depending on the gap length between the tools. With an increase in the distance between the two deforming tools from 100 to 300 mm, the level of compressive stresses in all models increases by 1.5–2 times, depending on the matrix-rotation speed.

Key words: copper, wire, twisting, drawing, stress state, modelling.

У цій статті досліджується вплив нової комбінованої технології оброблення мідного дроту на напружений стан. Дана технологія полягає в деформуванні дроту в рівноканальній ступінчастій матриці, що обертається, та подальшому волочінні. Моделювання деформації проводилося за темпе-

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ратури навколишнього середовища. Для оцінки впливу ступеня скручування заготівки на величину середнього гідростатичного тиску швидкість обертання матриці змінювалася в межах 6, 18 і 30 об/хв, віддаль між двома деформувальними інструментами також змінювалася в межах 100, 200 і 300 мм. Результати моделювання показали обернену залежність інтенсивности стискальних напружень від швидкости обертання матриці та пряму залежність від величини зазору між деформувальними інструментами. Так, зі збільшенням швидкости обертання матриці рівень стискальних напружень у всіх моделях понижувався в 1,5–2 рази, залежно від довжини зазору між інструментами. У разі збільшення віддалі між двома деформувальними інструментами зі 100 до 300 мм рівень стискальних напружень у всіх моделях зростає в 1,5–2 рази, залежно від швидкости обертання матриці.

Ключові слова: мідь, дріт, скручування, волочіння, напружений стан, моделювання.

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1. INTRODUCTION

The modern market economy imposes fundamentally new requirements on product quality. Now, the survival of any enterprise and the stable position of its goods and services in the market are determined by the level of competitiveness. Competitiveness is related to two indicators: price and product quality. The competitiveness of a product is understood as a set of qualitative and cost characteristics of a product that meet the specific needs of the buyer at a given time and compare favourably with similar products produced by competitors.

The main way to increase the competitiveness of wire is to introduce innovative developments and technologies into existing production, which will allow producing higher-quality wire at lower costs [1–5]. Therefore, the current steadily growing demand for high-quality wire requires wire manufacturers to take a new approach to further development and improvement of drawing technology.

The need to develop and introduce into production innovative technologies for the manufacture of wire with high strength and plastic properties determines the relevance of this study.

A good option may be the principle of deformation combination, when, as a result of combining two processes, it becomes possible to increase the plastic characteristics of the metal [6–10]. It is known from the practice of metal forming that the application of the alternating strains makes it possible to increase the plastic resource of metals due to the grain reorientation, the appearance of new sliding planes and a decrease in energy along grain boundaries. This mechanism is because the dislocation structure formed under a certain deformation pattern is disrupted when the deformation pattern changes. Such deformation treatment does not reduce the dislocation density in the metal, but by redistributing them, it changes the dislocation structure. The involvement of additional sliding planes shifts the moment of complete embrittlement to the area of increased total compression. As a result, the yield strength decreases and the wire ductility increases. This is because plasticity and deformability are largely determined by the density and distribution of crystalline structural defects (mainly dislocations) in the metal volume, which accumulate during progressive deformation. Therefore, it is necessary to create such deformation conditions so that local peak stresses are always removed, even before the crack originates.

Nanostructuring processes are one of the most progressive ways to improve the complex of mechanical properties of structural materials, allowing significant modification of the properties of alloys without changing the chemical composition [11–17]. However, the unique combination of particularly high strength and at the same time sufficient plasticity of ultrafine-grained materials requires a unique development of methods for their production. Therefore, many scientists have been trying for a long time to combine traditional drawing with methods of severe plastic deformation, which make it possible to obtain an ultrafine-grained and nanostructure [18–22].

One of these combined technologies is a technology that combines ECAP and traditional drawing (ECAP-drawing) [23–25]. The deformation technology being developed in this article represents a further development of the combined 'ECAP-drawing' process. In this technology, the key feature is the rotating ECA matrix. Due to this, the workpiece, in addition to deformation at the stages of ECAP and drawing, receives a certain increase in deformation due to twisting in the gap between two deforming tools.

The practical significance of the study lies in the possibility of introducing improved technology into existing drawing mills by simply adding one node, without significant changes in the mill design or deformation technology.

2. EXPERIMENTAL

The possibility of implementing combined loading using traditional drawing was studied using computer modelling. The study was conducted using the DEFORM-3D software package, which takes into account sufficient resources to solve the tasks and a user-friendly interface that allows you to output data in the form of graphs and images with high computational accuracy.

Consideration of the stress state is important in the study of any deformation technology. From the point of view of the processed material, the study of the stress state allows to assess the resulting stress distribution over the entire workpiece volume and make the necessary adjustments to obtain the most optimal distribution picture (for example, to reduce the level of tensile stresses and increase the proportion of compression stresses). From the perspective of a deforming tool, the study of the stress state allows to assess the overall stress level that occurs and identify the possibility of equipment failure due to violation of strength conditions.

In addition, in this case, it is necessary to take into account the noncumulative nature of all stress state parameters. Unlike the strain state, stress parameters tend to reset after the load is removed. Therefore, the most appropriate way to study the stress state is to consider the workpiece at the time of simultaneous deformation in both tools. This will allow examining in detail the patterns of stress distribution both in the deformation zones and in the gap between the tools. In this case, the most advantageous position is the longitudinal section of the workpiece, which allows to consider the stresses that arise both in the transverse direction (in height) of the workpiece and in the longitudinal direction (in length).

The deformation speed v_1 applied to the front end of the workpiece and equal to 500 mm/s was taken as the initial parameter. In the fibre, the initial diameter of 7 mm is reduced to 6 mm. In accordance with the law of constancy of second volumes, the velocity v_{0-1} will be equal to 367 mm/s. The velocity v_0 applied to the rear end of the workpiece is 280 mm/s. At the same time, it was decided to vary the value of the angular velocity of rotation of the matrix in order to assess the effect of the workpiece twisting level on the stress state. The following values of the matrix-rotation speed were set: 6, 18, 30 rpm. A geometric parameter the distance between two deforming tools was also varied. This variation was designed to evaluate the distribution of workpiece twisting intensity in the interval between tools with unchanged kinematic parameters. The following values of the distance between the matrix and the drawing die were set: 100, 200, 300 mm.

3. RESULTS AND DISCUSSION

Figure 1 shows the patterns of stress distribution in the workpiece section with a distance between the matrix and the drawing die of 100 mm at different matrix-rotation speeds.

Comparing the obtained results, it can be noted that the stress distribution is quite identical both in the deformation zones and in the gap between the instruments. At all matrix-rotation speeds, an absolutely identical pattern is formed in the ECAP deformation zone, both in terms of the nature of the stress distribution and their values. This is because the influence of the matrix-rotation speed in this defor-

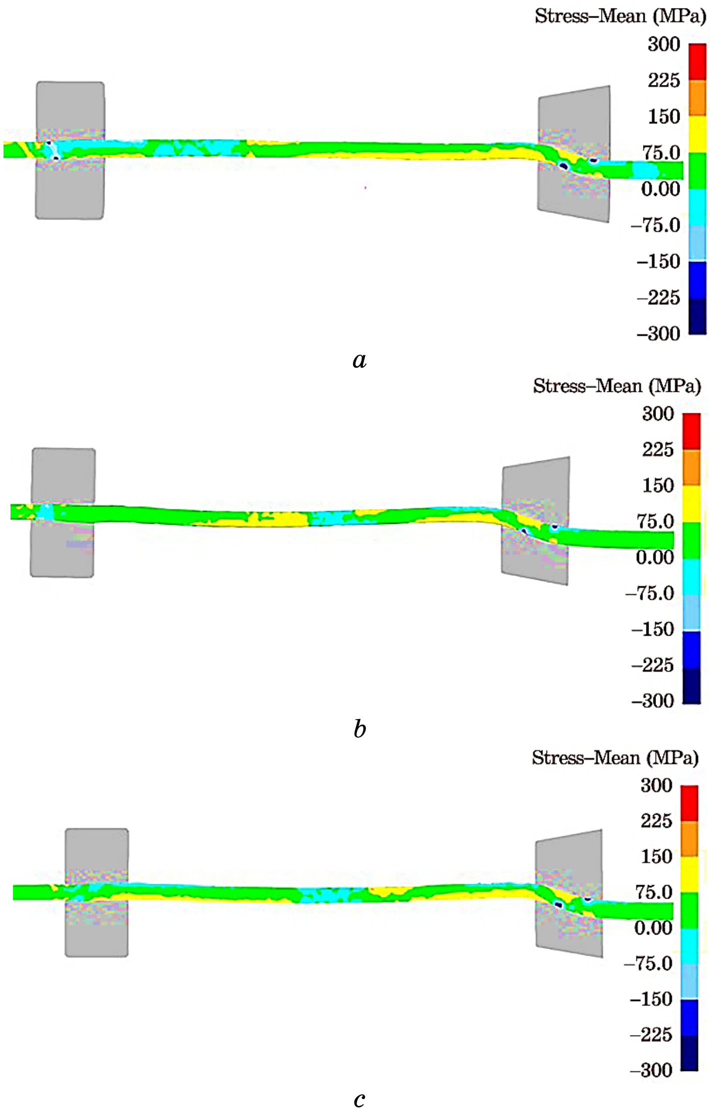

Fig. 1. Stress distribution in the workpiece section with a distance between the matrix and the drawing die of 100 mm at different matrix-rotation speeds: 6 rpm (*a*), 18 rpm (*b*), 30 rpm (*c*).

mation zone is practically absent due to the free rear end of the workpiece, which rotates with the matrix.

Due to the presence of tension in the matrix, only small areas of contact between the workpiece and the tool occur, compressive stresses in the range of –230––250 MPa occur in these zones. Zones of tensile stresses in the range of 80–100 MPa are created in opposite sections.

In the interval between the tools, the stress values are also approximately the same, namely, in the stretching zones, the stress level is of 60–80 MPa, and in the compression zones, the stress level is of –20––50 MPa. The main difference here is the nature of the distribution of tensile and compressive stresses, which is the result of the influence of the matrix-rotation speed. Comparing all three pictures in Fig. 1, it can be noted that, with an increase in the matrix-rotation speed in the considered interval between the tools, a stress distribution along a helical line is observed, whereas at a speed of 6 rpm this distribution is almost linear in length.

The first serious differences in the models are observed in the drawing deformation zone, which is associated with a change in the matrix-rotation speed, which, in turn, has a direct effect on the workpiece twisting intensity in the interval between tools. With an insignificant rotation speed of the ECA matrix of 6 rpm, the drawing deformation focus differs little from the classical focus, when compressive stresses prevail in the contact zone of the workpiece and the drawing (under these conditions, their level is approximately of –140––150 MPa). With an increase in the rotation speed of the ECA matrix, the level of twisting of the workpiece increases, as a result of which the level of compressive stresses decreases. This phenomenon is a well-known fact, when the torsion factor reduces energy costs during drawing [4]. As a result, at a matrix-rotation speed of 18 rpm, the level of compressive stresses in the drawing deformation zone is approximately of –100––120 MPa, and at a matrix-rotation speed of 30 rpm, the level of compressive stresses is approximately of –60––70 MPa.

Figure 2 shows the patterns of stress distribution in the workpiece section with a distance between the matrix and the drawing die of 200 mm at different matrix-rotation speeds.

An increase in the gap between deforming tools has practically no effect on the parameters of the stress state in the ECAP deformation zone and in the gap between the tools. For all values of the matrix fusion rates, patterns similar to the previously considered models in Fig. 1 are observed in these zones. Significant differences are observed only in the drawing deformation zone. Here, the inverse dependence of the intensity of compressive stresses on the matrix-rotation speed is preserved. However, a comparison of two groups of models with different values of the gaps between the tools revealed a direct relationship of this parameter with the intensity of compressive stresses—in all three models, the level of compressive stresses in the drawing area had increased of 25–35%. Despite the fact that increasing the matrix-rotation speed reduces stresses, the overall increase is associated with an increase in the total working of the metal along the section, *i.e.*, with its hardening due to longer workpiece twisting.

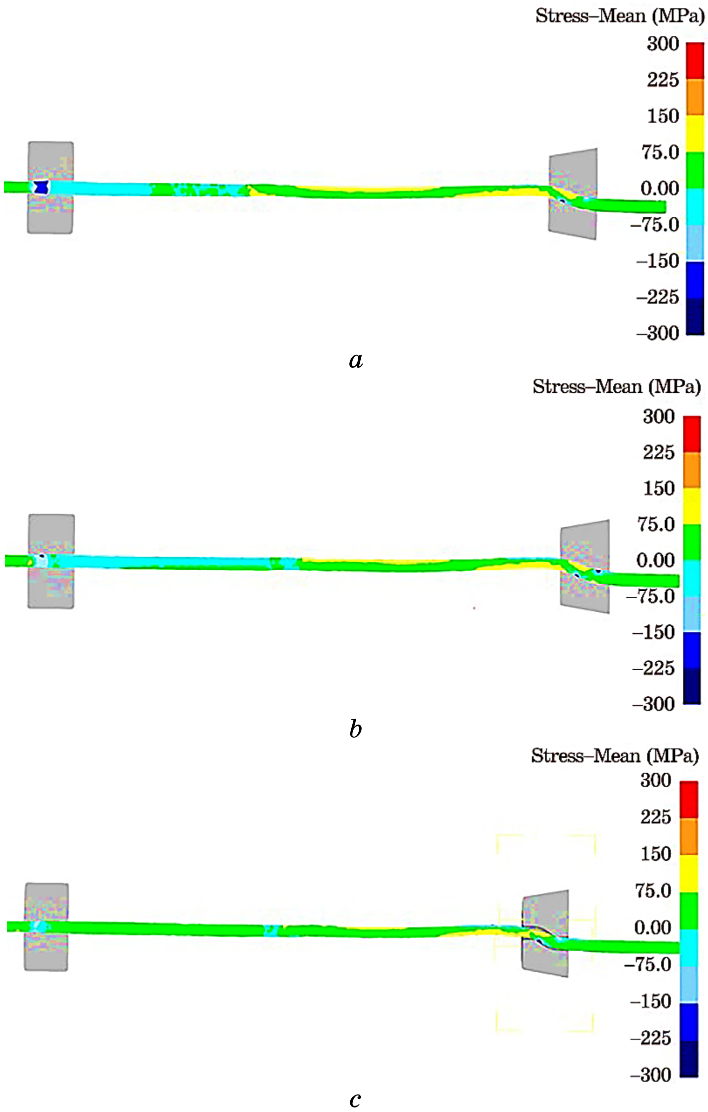

Fig. 2. Stress distribution in the workpiece section with a distance between the matrix and the drawing die of 200 mm at different matrix-rotation speeds: 6 rpm (*a*), 18 rpm (*b*), 30 rpm (*c*).

Figure 3 shows the patterns of stress distribution in the workpiece section with a distance between the matrix and the drawing die of 300 mm at different matrix-rotation speeds.

A further increase in the gap between the instruments from 200 to 300 mm preserves the previously identified dependences. There is still

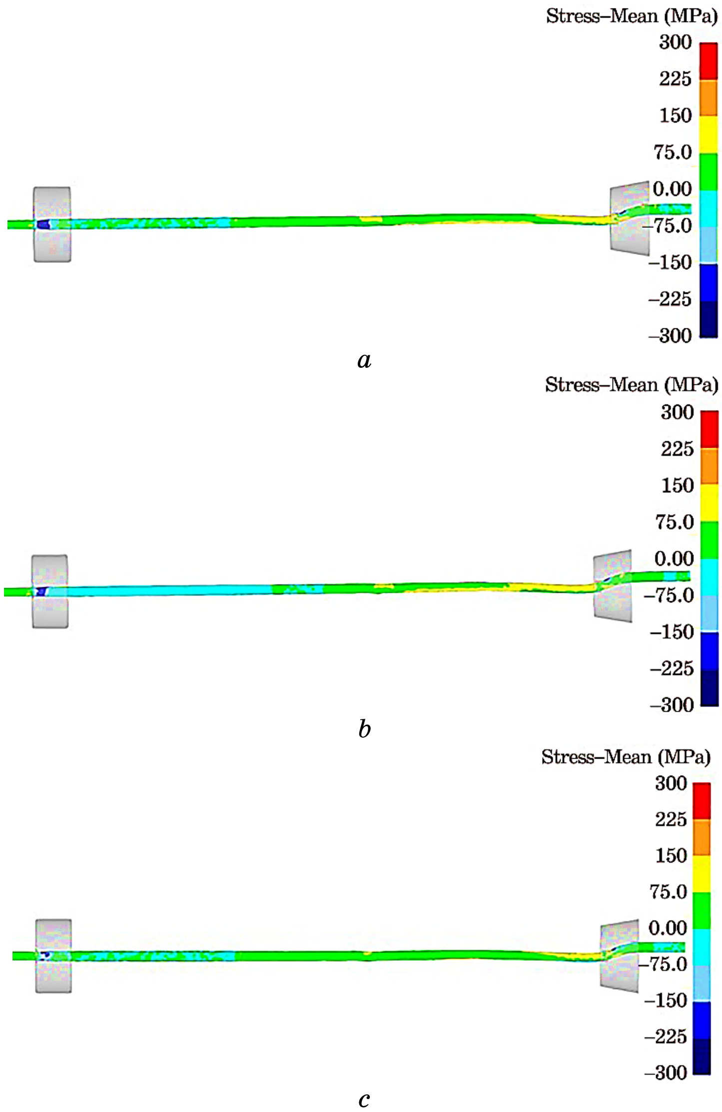

Fig. 3. Stress distribution in the workpiece section with a distance between the matrix and the drawing die of 300 mm at different matrix-rotation speeds: 6 rpm (*a*), 18 rpm (*b*), 30 rpm (*c*).

an inverse dependence of the intensity of compressive stresses on the matrix-rotation speed and a direct dependence of the intensity of compressive stresses on the magnitude of the gap values.

Since the differences in all the considered models were revealed only at the drawing stage, for this zone, all the stress values obtained were

TABLE 1. Stresses in the drawing area, MPa.

Parameter	6 rpm	18 rpm	30 rpm
100 mm	–140––150	–100––120	–60––70
200 mm	–160––170	–120––140	–90––110
300 mm	–220––240	–160––180	–140––160

summarized in Table 1.

4. CONCLUSION

In this article, the stress state is considered during the implementation of a new combined technology for copper wire processing. The key feature of the new technology is the wire deformation in a rotating equal-channel step matrix and subsequent drawing. The analysis results of the average hydrostatic pressure revealed an inverse dependence of the compressive stresses intensity on the matrix-rotation speed and a direct dependence on the gap magnitude between the deforming tools. Thus, with an increase in the matrix-rotation speed, the level of compressive stresses in all models decreased by 1.5–2 times, depending on the gap length between the tools. With an increase in the distance between the two deforming tools from 100 to 300 mm, the level of compressive stresses in all models increases by 1.5–2 times, depending on the matrix-rotation speed.

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