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Article

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FORMING OF PROPERTIES COMPLEX OF COPPER WIRE BY THE METHOD OF COMBINED DEFORMATION BY TORSION AND TENSION

The object of research is the mechanical properties of copper wire M1 for electrical applications, subjected to combined torsional deformation with tensile tension. One of the most problematic aspects in the manufacturing of such a wire is its fracture during processing due to low strength and ductility. DSTU EN 13602:2010 regulates the ultimate tensile strength, relative elongation, the number of bends before fracture and the number of twists until failure. To increase the service life of the product it is necessary to increase strength and plastic properties.

The methods of influence on the material by combined plastic tensile deformation with tensile was used in the study, the mechanical characteristics (ultimate tensile strength, true deformation before failure, relative elongation, relative reduction in area) and electrical conductivity were determined. Statistical analysis tools were used for modeling and graphical displaying of data.

The proposed approach allows to select the modes of combined torsional deformation with tensile, providing the optimal combination of tensile strength and relative narrowing of M1 grade copper wire. Under certain modes of such deformation, with increasing degree of deformation, it is possible to increase the strength characteristics and at the same time obtain high values of plasticity.

The obtained results of approbation of different combined deformation modes allow to consider it an effective tool for achieving high values of true rapture stress and ultimate deformation in order to improve the service characteristics of the deformed wire. It is shown that relaxation processes occur during such treatment, which leads to a decrease in stresses and a sharp increase in plastic characteristics. Clarification of the mechanisms of the characteristics formation allows to control the features of the structure and, accordingly, the level of mechanical properties to obtain a wire that combines high strength with high toughness. This makes it possible to develop deformation modes to obtain copper wire with special properties depending on customer requirements, for example: strong wire with low electrical resistance.

Keywords: *M1 grade copper wire, electrical application, combined plastic deformation, resistivity, stress relaxation.*

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1. Introduction

Copper wire is practically used in such devices and equipment as power plant generators, electric motors, power lines, radio and electronic components, etc. as a material of electrically conductive elements. The main advantages of copper wire are: plasticity and ductility, high electrical and thermal conductivity. One of the most problematic moments in the manufacturing of such wire is its fracture during processing due to lack of strength and ductility. To increase the service life of the product it is necessary to increase simultaneously the strength and plastic characteristics. Regulatory documentation, in particular, DSTU EN 13602:2010 regulates not only mechanical properties (tensile strength, relative elongation and relative reduction in area), but also technological (number of bends and number of twists to complete failure).

Recently, the methods of combined plastic deformation, which consist in the simultaneous action of several types of loading, are widely used to solve such problems. For example, such as: torsional compression, torsional tension, torsional drawing, shear rolling, etc. [1, 2]. Thus, the imposition of torsion on drawing allows creating a scheme of combined deformation with a complex stress state, which allows to implement new approaches to the formation of structure and properties. Ultimately, this treatment allows getting both strength and plastic wire. However, adjustment of drawing with torsion modes is an extremely time consuming and expensive process. Therefore, primary information about the special properties can be obtained, for example, by applying a rather simple torsional tensile scheme. Such information can be extremely important in the development, adjustment and use of industrial combined deformation schemes.

2. The object of research and its technological audit

The object of research is the mechanical properties of M1 copper wire for electrical applications, subjected to combined torsion and tension deformation. The length of the samples was l=150 mm, diameter d=3.0 mm. Since the samples initially did not meet the requirements of consumers in terms of strength and plastic characteristics, these samples were subjected to recrystallization annealing at a temperature of 500 °C for 1 h, and then they were deformed by tensile torsion. From a technical point of view, torsion provides great opportunities for changing the degree of deformation and the sign of the applied load, so two types of experiments were performed:

1) tension and unidirectional torsion (hereinafter TUT);
2) tension with multidirectional torsion (hereinafter TMT).

In the case of TUT, clockwise torsion under axial loading was first performed, then stopping without unloading and torsion for a different number of rotations in the same direction was fulfilled. At the TMT it was carried out: at first, tension and torsion clockwise, then stopping without unloading, and torsion counterclockwise. Thus, the TUT and TMT processing modes consisted of two stages:

1. For TUT: $N=N_1+N_2=50$, where $N_1=25$ and $N_2=1\div25$, in both cases this is the number of rotations clockwise.

2. For the TMT scheme: $N=N_1+N_2=50$, but $N_1=25$ is the number of rotations clockwise, and $N_2=1\div25$ is the number of rotations counterclockwise.

3. The aim and objectives of research

The aim of research to develop a scheme for the combined deformation of M1 copper wire by torsion with tension, which makes it possible to increase the complex of mechanical and service characteristics of the wire.

To reach the goal, the following tasks were set:

1. To study the relationship of mechanical properties with the mode of combined deformation according to the TUT and TMT schemes.

2. Determine the dependence of the ultimate tensile strength, true fracture strain, relative reduction in area and elongation, electrical resistance on the degree of deformation during TUT and TMT treatments.

3. Propose the directions for improving of the productive process, taking into account the requirements of customers.

4. Research of existing solutions to the problem

Over the past 10 years, extended knowledge has been accumulated concerning the effect of combined plastic deformation on the processes of structure formation. The fundamental possibility of obtaining of new structural states, leading to a simultaneous increase in strength and plasticity has been shown [1, 2]. However, as noted in [1], the accumulated data mainly concern combined deformation schemes implemented in laboratory conditions. These are torsion in Bridgman anvils, equal channel angular pressing, screw extrusion [2, 3]. Works [4, 5] are devoted to the mechanisms of structure refinement in industrial steels using schemes of combined plastic deformation with shear in laboratory conditions. Changes in the morphology of the structure are shown, such as: grain refinement, an increase in the boundaries of high-angle misorientation, an increase in the density of dislocations, the formation of twins and shear bands. These changes in the structure correlated with changes in microhardness, yield strength, and tensile strength. However, the authors can not to find a deformation regime in which, with an increase in strength, sufficient technological plasticity would be preserved. Thus, in general, the work does not support the idea of plasticity increasing with the help of combined deformation. An alternative solution of the problem is proposed in [6]. This work is dedicated to high-pressure torsion (HPT) processing of high-purity aluminum according to several schemes: deformation in the forward direction with monotonic HPT (m-HPT) and with cyclic HPT (c-HPT) with a change in the direction of deformation. Experiments show that microstructure development is slower with c-HPT in the sense that the increase in defect density is lower than with m-HPT. It is concluded that reversing the direction of deformation during HPT processing makes it possible to manipulate the hardness values obtained during HPT. However, the paper has not fully disclosed: is it possible to use strain reversal to reduce stresses in the material during deformation in order to increase its technological plasticity? In addition, the question of the optimal deformation regime for providing a set of properties remained unresolved. Therefore, undoubtedly valuable data cannot be used for practical purposes.

The authors of [7] showed that equal channel angular pressing (ECAP), helical equal channel extrusion with an elliptical cross section (ECSEE) and torsion deformation (TD) have proven themselves as effective methods for grain refinement. To compare the characteristics of grain refinement by these technologies, experimental studies of the evolution of microstructure and mechanical properties were carried out using optical microscopy (OM), transmission electron microscopy (TEM) and microhardness tests. The authors of [7] emphasized the importance of the formation of shear bands, dislocation forests, grain boundaries with a large misorientation angle, and subgrains. Various TEM morphological structures have been discussed in terms of the influence of deformation modes, including bend-torsion, extrusion torsion, and pure torsion, on microstructure evolution. It has been established that ECAP differs from ECSEE and TD in the distribution of microhardness in the radial and circumferential directions. In this work, it is shown that shear deformation is one of the effective methods of grain boundary engineering. However, no conclusions have been drawn about which type of deformation is more effective in terms of the formation of a particular structure and properties.

The assertion that shear deformation is an effective way of grain engineering can be considered using the example of a simpler scheme of tensile deformation with torsion. For example, in [8], the evolution of the microstructure and the fracture behavior of austenitic stainless steel 316L (ASS) deformed by tension with torsion at room temperature were studied. According to the observations of the authors of the work, under tension with torsion, the grain size decreased with increasing of the shear strain. In addition, the microtexture showed a preferred orientation with increasing of the shear stress. Metastable austenite undergoes a phase transition with increasing shear stress. The dislocation density increased significantly due to shear deformation. In addition, as the shear strain accumulated during such combined deformation, the dislocation structure is developed and subgrains are appeared. The result showed that torsion deformation plays an important role in improving the complex of characteristics and evolution of the microstructure of a sample subjected to tensile deformation. However, the question remains: to what degree of deformation should such processing be carried out and how will such combined deformation affect the mechanical properties of the steel?

Thus, the results of the analysis allow to conclude that the combined deformation makes it possible to refine the grain more strongly and to strongly transform the structure, but the question of what will happen to the material when the sign of the load changes is not completely clarified. Will this have a positive effect on the level of mechanical properties? The described works practically do not have actual confirmation of the growth of plastic characteristics with a change in the sign of the load. Among the main directions for solving this problem, identified in the resources of world scientific periodicals, work [8] can be singled out, but it does not consider what kind of such deformation schemes can be applied in the mass production of metals and alloys.

An alternative approach to using the revealed regularities is considered in works devoted to the implementation of combined deformation effects during realization of traditional technological rolling processes. This allows the use of high-performance mass production technologies. It was shown in [9, 10] that it is shear deformations realized during asymmetric rolling that make it possible to obtain a finely dispersed and uniform structure. However, the authors of the study [10] note that in order to achieve a positive effect, it is necessary to change the direction of action of shear stresses during rolling; otherwise, the formation of structural inhomogeneity and a decrease in plastic characteristics are observed. Another variation of shear rolling is the radial shear rolling scheme. It was shown in [11, 12] that shear deformations contribute to the refinement of the structure of various alloys based on titanium and stainless steels. A common limitation of these technologies is that the deformation of materials takes place at high temperatures, which facilitates deformability, but leads to a decrease in the effectiveness of hardening due to the development of recrystallization. The scheme of radial shear rolling is also characterized by the complexity of the design of deforming devices. Therefore, the schemes considered are rather modifications of existing technological processes, then new ones, and do not allow to obtain fundamentally new structural states of deformable materials.

A separate issue that has not been sufficiently studied is the effect of severe and combined plastic deformations on the physical properties of materials, in particular, on electrical conductivity. The authors of [13] found that the use of radial shear rolling for the production of bars from a copper alloy of the Cu–Ni–Cr–Si system makes it possible to obtain a high-strength disperse structure, but additional annealing is required to restore electrical conductivity, which partially reduces the effect of hardening. In [14], the influence of severe plastic deformation by compressive torsion and equal-channel angular pressing on the properties of electrical copper was studied. According to the work, the combination of these treatments allows obtaining high strength while maintaining the electrical conductivity at the level of 99.3 % of the values for the material before deformation. However, the mechanisms of this effect have not been studied, and the deformation scheme itself is inefficient and expensive.

Thus, despite the large number of works, plastic deformation schemes, in which are possible to obtain a bulk amount of deformed material, have not been sufficiently studied. This is primarily due to the fact that experiments to create and adjust combined deformation processes are quite laborious, expensive and long-term.

From the conducted literature analysis, it follows that it would be useful to find such a solution that could serve as a cheaper, but at the same time reliable way to conduct model experiments, the results of which can be transferred to real production using combined deformation schemes.

5. Methods of research

For determination of mechanical characteristics, deformed wire samples were subjected to uniaxial tensile test. A sample 75 mm long was clamped in grippers with grooves and tested on a UTM-100 tensile machine (Italy) at uniaxial loading with the recording of loading graphs. The study was carried out according to the method described in [15]. After processing, the obtained mechanical characteristics of the material are evaluated: ultimate tensile strength σ_{UTS}, relative elongation δ, relative reduction in area ψ, true deformation at the moment of fracture (calculated as the logarithm of the ratio of the initial cross section area to the final), electrical resistivity. To obtain statistical data, parameters of tests were fixed in each case on 5 samples, after which the average value was calculated.

6. Research results

The results of the experiments are shown in Fig. 1–4. Fig. 1 shows the tensile strength, Fig. 2 – true deformation at fracture during TUT and TMT torsion.

An analysis of changes with an increase in the number of rotations shows an increasing in the tensile strength both in the case of TUT and in the case of TMT processing. With the TUT scheme (Fig. 1, *a*), a gradual increase in the values of the ultimate strength is observed in accordance with the Taylor theory [16, 17]. It was shown in [17, 18] that at the initial stage of deformation, the density of randomly located dislocations increases. However, the tensile strength growth rate starts to decrease approximately from $N_1=25$. The decrease in strengthening at this stage can be explained by the interaction of mobile dislocations, formed during uniaxial tension, and dislocations at the boundaries of weakly misoriented cells that appeared during torsion.

In Fig. 2, *a* the dependence of the true strain at fracture during TUT processing is shown. The change in behavior of a parameter is similar in nature to changes in the tensile strength. At first, it is possible to see a sharp decrease in true strain to $N_1=25$, and then the curve becomes flat and the parameter values fluctuate within small limits up to $N_2=50$.

Let's consider the mechanical properties of TMT samples twisted 25 turns in one direction and a certain number of turns in the opposite direction. Analysis of Fig. 1, *b* and Fig. 2, *b* shows that the mechanical properties of copper samples change non-linearly with an increase in the degree of total deformation. Attention is drawn to the unusual nature of the dependences of mechanical properties on the number of reverse turns. In the case of TMT, the dependence of the tensile strength and true deformation has the character of curves with a minimum. At low values of N_2, a decrease in the ultimate tensile strength by approximately 40 units is observed. This happens when we are just starting to rotate in the opposite direction. As for the values of true strain, at small values of N_2, its sharp increase begins (by a factor of 5), and then, at N_2 from 7 to 25 revolutions, the curve becomes flatter.

Such behavior of the tensile strength and true strain at fracture with a small number of reverse turns can be caused by the introduction of fresh dislocations into the structure upon changing the loading scheme, which was observed by the authors in [19, 20]. Fresh dislocations, in their opinion, interact with weakly misoriented cells, which lead to a change in cell sizes. Partial annihilation of dislocations occurs in the dislocation walls and, as a result, the strength of material decreases. The consequence of such interaction may be some decrease in the yield strength and a significant increase in crack growth resistance [15, 17]. Data in Fig. 1 and Fig. 2 clearly shows significant differences in the changes in the ultimate tensile strength and true deformation with increasing *N* for different deformation schemes.

Data in Fig. 3, *a* and Fig. 4, *a*, shows the dependence of the relative reduction in area and elongation on the number of rotations during the TUT. It can be seen that they sharply decrease from about $N_1=5$ revolutions. It is widely known [1, 17, 20] that the values of relative reduction in area and elongation determine the technological plasticity of metals. Therefore, it is possible to assume that a sharp decrease in their values characterizes the loss of metal plasticity, which is unequivocally confirmed by changes in the mode of fractures [15].

With the TMT scheme, the dependence of the relative elongation is similar to the TUT scheme, however, the behavior of the relative reduction in area differs fundamentally. A complex and unusual dependence of the relative reduction in area on the number of reverse turns is shown in Fig. 3, *b*. The beginning of torsion in the counterclockwise direction at $N_2=1\div7$ leads to an increase in the relative reduction in area to values very close to characteristic of an unreformed material. It is well known in the practice of drawing production that the technological drawability correlates precisely with the values of the relative reduction in area. If the value of this parameter is sufficiently high, then it is possible to carry out further drawing to smaller diameters without annealing. Therefore, the discovery of such an effect may be of interest to manufacturers. With a further increase in the number of reverse turns (up to $N_2=25$), the increase in the relative narrowing decreases sharply.

As was shown in [15], an increase in plasticity when using the TMT scheme manifests itself at the macrolevel in the restoration of the ability of samples to necking and at the microlevel in changing of fracture mode to ductile type. Changing the reverse torsion loading scheme allows blocked dislocations to find other ways to move.

The obtained experimental data concerning the effect of various modes of TUT on the structure and properties of copper M1 made it possible to establish the classical picture of an increase in the strength characteristics and refinement of the grain structure of the wire with an increase in the degree of deformation.

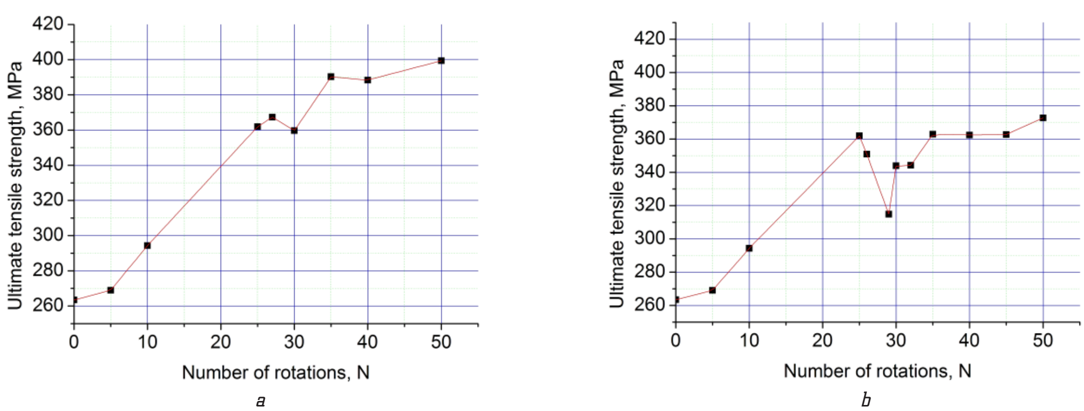


Fig. 1. Influence of the number and direction of rotation on the ultimate strength: *a* – TUT; *b* – TMT

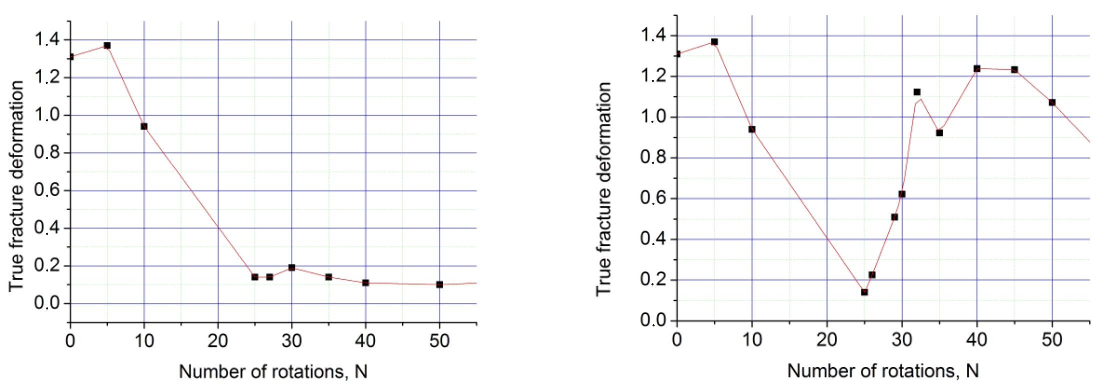
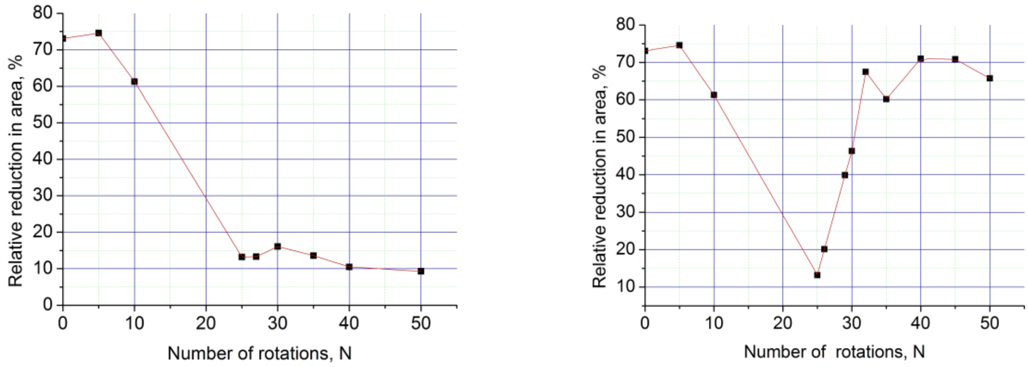
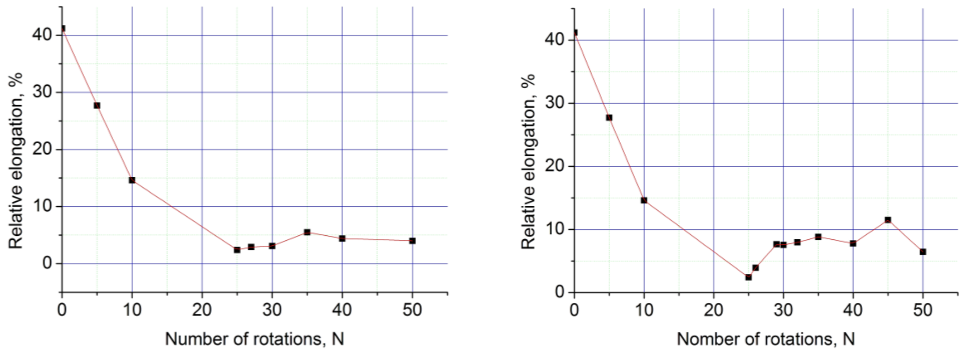


Fig. 2. Influence of the number and direction of rotation on the true deformation at fracture: *a* – TUT; *b* – TMT



a *b*

Fig. 3. Influence of the number and direction of rotation on the relative reduction in area: *a* – TUT; *b* – TMT



a *b*

Fig. 4. Influence of the number and direction of revolutions of rotation on the relative elongation: *a* – TUT; *b* – TMT

However, in the case of TMT deformation, the picture becomes more complex: in some cases, the changes are of a classical nature, and in some cases, the linear change in properties changes to the opposite with an increase in the degree of deformation. Such changes can be associated with a number of physical processes that occur in M1 copper during deformation, such as: dynamic recovery (movement of point defects), dynamic polygonization (movement of dislocations and low-angle boundaries), or dynamic recrystallization (movement of high-angle boundaries). Works [19, 20] show the effect of shear deformation included in the conventional drawing and rolling process. A specific feature of these experimental technologies is the reduction of structural anisotropy. This effect is associated with the application of shear, which causes the flow of metal to change its direction. It was shown that such technologies lead to a strong grain refinement, namely, to an increase in the proportion of small grains (less than 3 μm in size) and a decrease in the number of large grains. A large number of small grains with high-angle boundaries are registered. The formation of such grains is explained by the development of competing processes of large grains fractioning and continuous dynamic recrystallization. The result is a change in the type of grain boundaries from smooth to serrated and the formation of non-closed high-angle grain boundaries. In addition, it was demonstrated that a certain part of small grains provides grain boundary sliding. This ensures the implementation of additional mechanisms of plasticity, which leads to a simultaneous increase in strength properties and the preservation of technological plasticity. Probably, a similar situation takes place in this experiment. However, additional studies are required to accurately establish the mechanisms of increased copper ductility in TMT.

Important information for the analysis of the processes of structural changes can be obtained from the analysis of changes in the electrical resistivity of deformed samples. In addition to being the main characteristic of copper as an electrical material, electrical resistance is also a structurally sensitive characteristic. At a constant chemical composition of the material, an increase or decrease in the proportion of resistance is associated with a change in the concentration of defects in the crystal structure (vacancies, interstitial atoms, dislocations, subgrain and grain boundaries). In Fig. 5 example of the dependence of specific electrical resistance on processing parameters at TMT deformation scheme is shown.

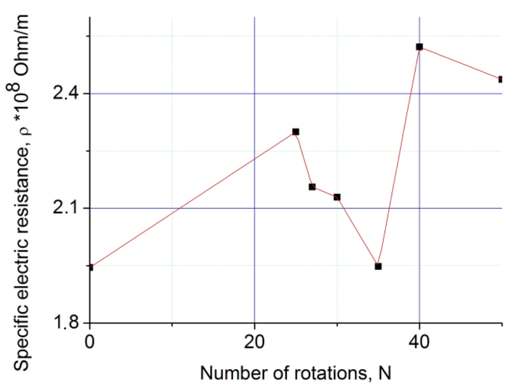


Fig. 5. Dependence of the specific electrical resistivity of the samples on the processing parameters at TMT scheme

As can be seen from the graph in Fig. 5, an increase in the degree of deformation during the torsion of the sample leads to an increase in its resistance by a factor of 1.18.

It is explained by a general increase in the concentration of defects in the crystal lattice during strengthening at deformation. However, after changing of the direction of sample torsion, in the range of rotations N_2 from 1 to 10, a decrease in electrical resistance is observed almost to the initial values, and then the increase in resistance resumes. It is important that the nature of the observed dependence is in many respects similar to the dependences of the true deformation and relative reduction in area on the processing parameters according to the TMT scheme (Fig. 2, *b*, Fig. 3, *b*, Fig. 4, *b*). These graphs show the restoration of plastic characteristics in a similar range of revolutions $N_2=1\div15$. This suggests that when the direction of deformation is changed, processes occur that lead to a decrease in the concentration of defects in the crystal structure. However, the nature of these mechanisms requires further investigations.

7. SWOT analysis of research results

Strengths. The positive effect of the research consists in the establishing of the complex nature of mechanical properties dependence on the processing mode according to the TUT and TMT schemes. Establishing the dependence of the change in relative reduction in area and strength on the number of rotations N_2 at TMT opens up the possibility of processing the wire in order to obtain special properties.

Weaknesses. The weak side of the research is that in order to implement the results in production, additional research will be required on the effect of drawing with torsion on the properties of copper wire in the flow of a drawing equipment.

Clarifications will also require questions about the nature of changes in the fine structure during TMT, which will entail the use of high resolution and expensive research methods involving an electron microscope.

Opportunities. From the foregoing, it follows that the prospects for further research consists in establishing the details of the mechanisms for the formation of unusual properties of copper wire during TMT processing. This will reduce the adjustment time of the technology when it is introduced into production route and permits to have a purposefully influence the level of properties of the finished wire.

Additional opportunities for the introduction of this technology into industry can bring the possibility to eliminate the intermediate annealing in the production of wire, which will significantly save on working time and costs for energy.

Threats. However, to obtain an economic effect, it will be necessary to go through the stage of implementation and testing of work in real production conditions.

8. Conclusions

1. It is shown that some modes of combined deformation with the TMT scheme make it possible to obtain a wire of high strength and sufficient ductility, which makes it possible to continue deformation of the wires without stopping production and performing annealing. This is especially important in the case of small diameter wire production.

2. The nonmonotonic nature of the dependence of mechanical properties on the degree of TMT deformation has been established. Deformation of the copper wire M1 according to the scheme of multidirectional rotation with tension (TMT) the with value of the reverse rotations N_2 more than 7 turns makes it possible to obtain a strengthened wire with relative reduction in area values close to the values in the non-deformable. Strength at this conditions increases compared to the initial state by 1.25–1.3 times and relative elongation values of 1.8–1.9 exceed the value in the wire deformed according to the scheme of unidirectional torsion (TUT). The established effects can permits drawing of wire to a smaller diameter without intermediate annealing.

The observed changes in the mechanical properties after TMT are the result of the activation of relaxation processes in the deformed structure, which leads to the decreasing of the internal stresses level and plasticity characteristics growth.

3. Established peculiarities of structure and properties changes during combined plastic deformation with multidirectional torsion make it possible to control a complex of mechanical characteristics. This makes it possible to use the treatment mode to obtain consumer-demanded copper wire properties, for example: a strength, ductile wire with a reduced increase in electrical resistance.

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