Физика и техника высоких давлений 2015, том 25, № 3–4

PACS: 61.66.–f, 62.20.–x

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DRAWING WITH SHEAR AS AN EFFECTIVE METHOD OF THE CONTROL OF THE STRUCTURE AND THE PROPERTIES FOR LOW-CARBON STEEL

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Received September 15, 2015

Technology of drawing with shear has been developed for manufacturing of low-carbon steel wire without annealing. It has been established that a specific feature of the presented technology is a reduction of the structure anisotropy and an increase in the plasticity resource. This effect is associated with shear that forces a change of the metal flow direction.

Keywords: drawing with shear, structure, properties, severe plastic deformation

Розроблено технологію волочіння зі зсувом для виготовлення дроту з низьковуглецевої сталі без відпалу. Встановлено, що особливістю запропонованої технології є зниження анізотропії структури та збільшення ресурсу пластичності. Цей ефект пов'язаний зі зсувною деформацією, яка викликає зміну напрямку течії металу.

Ключові слова: волочіння зі зсувом, стуктура, властивості, інтенсивна пластична деформація

1. Introduction

There is currently significant commercial interest in the development of materials with ultrafine grain (UFG) structures for structural applications [e.g. 1]. To obtain the materials with the UFG structure, different methods of severe plastic deformation (SPD) with shear are used both in a heated state and in a cold one [2]. Equal-channel angular pressing, multidimensional forging, twist extrusion and combinations of these methods with subsequent rolling, upsetting, drawing etc. are the most widely used [2–4]. The application of these processing methods allows substantial increase in the strength of the material at a certain conserved level of plasticity [5].

However the mentioned combinations of the methods cannot be realized in the wiredrawing. For all that, the industry is very interested in obtaining new technological and operation characteristics of long-length wire products [6,7]. One of the restrictions encountered when producing an UFG-structured wire is that the amount of the produced materials by the above-listed SPD methods is of tens of kilograms and tons. By contrast, the required capacity of drawing production is about hundreds of thousands tons. In this connection the technologies of mass production of the metal with enhanced properties and lower power consumption are currently under development [8,9].

It has been shown that combination of different scheme of deformation reveals new facilities of steel treatment [8,10]. A solution of the problem for long-length wire products can be in use of drawing with shear. An increase in the plasticity resource of rod and wire allows possible cheapening and simplification of the manufacturing technology at the expense of elimination of the intermediate annealing.

In [6,11–18], different methods of severe plastic deformation of long-length metal products of varied shape are described. The works [13,14,17] are of special interest.

The authors of [13] consider the application of sign-alternating bending of cold-drawn steel wire without an additional heating. The main advantages of the method are continuity and possible application for production of long-length products with increased mechanical properties.

In [14], a method of plastic formation of the structure in long billets and the installation for its realization is presented. The work of the equipment is based on sign-alternating deformation within the intersecting channels. The deformation zone in the billet is formed due to the displacement of the axes symmetry of channels with uniaxial tension. Being discontinuous, this method allows to produce long products of several meters in length. Its advantage is formation of a fine-grain structure. Nevertheless the deforming block is even more complex than in the case of [13]. Besides, neither of methods [13,14] permits manufacturing of a wire of small diameter.

One more drawing-based method of manufacturing long products with UFG structure is presented in [17]. Its main advantage is continuity of the process and possible application in mass drawing production. Its demerit is labor intensity of drawing, because of utilization of a complex technical unit. The main disadvantage is required dismounting and new installation of the unit to replace the wire-drawing dies.

Techniques for the production of the fine-grained alloys are thus of considerable scientific and commercial interest. Of particular importance in this context are cost-effective approaches that can be used to produce large quantities of such materials [e.g. 19–21]. A combination of SPD methods with conventional deformation processes appears having a great potential in this area [7].

In this study, a feasibility of new drawing with shear technology for commercial wire production is evaluated [22,23]. To evaluate feasibility of the new approach, its effect on physical and mechanical properties and the grain structure was examined and compared with those of conventional wire-drawing.

2. Experimental procedure

The program material is consisted of commercial grade low-carbon steel whose nominal chemical composition is shown in Table 1. The material was produced as a hot roller bar with a diameter of 6.15 mm.

Table 1

Chemical composition of the wire of low-carbon steel, %

C	Mn	Si	S	P	Cr	Ni	Cu	N
0.071	1.98	0.84	0.015	0.018	0.015	0.009	0.016	0.0055
Ti	As	B	Al	V	Mo	W	Co	
< 0.005	< 0.005	< 0.0005	0.005	0.006	< 0.01	0.024	0.01	

The drawing with shear was carried out by using a specially designed dies promoting the «twist» character of material flow (the experimental die had axial twisting with the speed of 3 revolutions per minute). For comparative purposes, ordinary drawing was also conducted by using conventional dies. These two approaches were defined throughout as experimental and classical technologies, respectively. The drawing routes for both processes are detailed in Table 2. In all cases, the material was drawn at ambient temperature and no intermediate annealing steps were applied.

Table 2

Drawing routes of the wire produced by the experimental and classical technologies

Technology	Die diameter, mm
Experimental	∅6.15 → ∅5.45* → ∅5.0 → ∅4.7* → ∅4.20 → ∅3.85 → ∅3.30 → → ∅2.95 → ∅2.75 → ∅2.42 → ∅2.13 → ∅1.88 → ∅1.70 → ∅1.55
Classical	∅6.15 → ∅5.45 → ∅5.0 → ∅4.40 → ∅3.85 → ∅3.30 → ∅2.95 → → ∅2.75 → ∅2.42 → ∅2.13 → ∅1.88

*A die with shear (providing twist flow of the metal)

To characterize the metal structure imperfection, material density was measured by hydrostatic weighing with using the weigh scales AX-200 by Shimadzu. 10 mm-long samples of each diameter were measured six times. The relative error of this method was 0.3%. Such accuracy allowed us to detect microimperfections. The maximum changes in density, by increasing dislocation and vacancy densities, was 0.1%. In our experiment, we observed the density changes to be more than the accuracy of the method.

To establish the effect of the drawing strain on material strength, Vickers microhardness data were obtained by applying a load of 200 g for 10 s; at least 10 measurements were made to obtain the average value.

Microstructural observations were performed by optical microscopy and electron backscatter diffraction (EBSD). For optical microscopy, the microstructural specimens were mechanically polished in conventional fashion and finally chemically etched by using a 4% Nital solution. The quantitative estimation of the grain size and its fragments was made in both transversal and longitudinal directions. 100 measurements were made on every photo. The elongation ratio was calculated by the formula

$$k = D_1/D_2,$$

where D_1, D_2 (μm) were the grain lengths in the longitudinal section of the sample across the grain elongation and along it, respectively. The closer k to 1, the higher isotropy of the tested structure was registered.

A final surface finish for EBSD was obtained by electro-polishing in a solution of 65% orthophosphoric acid + 15% sulphuric acid + 6% chromic anhydride + + 14% water. The important electro-polishing parameters included: temperature 70–90°C, anodic current density 1 A/cm^2, voltage 23 V, and exposure 19 s.

EBSD analysis was conducted using a JSM-6490LV scanning-electron microscope equipped with HKL EBSD software. Depending on particular material condition, orientation mapping was performed using scan step size of 0.3 or 0.5 μm. To improve the reliability of the EBSD data, EBSD maps were «cleaned» using standard clean-up option of the HKL software. In addition, to eliminate spurious boundaries caused by orientation noise, a lower-limit boundary-misorientation cut-off of 2° was used. A 10° criterion was used to differentiate low-angle boundaries (LABs) and high-angle boundaries (HABs).

3. Experimental results

One of the specific features of the experimental technology is reduction of the structure anisotropy. Compared with the «experimental» samples in the longitudinal section, the anisotropy is expressed more in the «classical» samples: the ferrite grain is smaller, and the perlite colonies are stretched in stripes. The perlite colonies in the «experimental» samples are less elongated, but more rounded (Fig. 1). The same effect is observed in the cross-section. This fact is confirmed by the data about the elongation ratio while increasing the degree of deformation, see Table 3.

Table 3

Elongation ratio *k* for the low-carbon steel wire

Technology	*k*			
	∅6.15	∅5.0	∅3.9	∅1.55/∅1.88
Experimental	1	0.47	0.72	0.28
Classical		0.65	0.44	0.12

The classical drawing technology is associated with a decrease in the elongation ratio when the diameter of the samples is reduced. The reason is that drawing is a kind of uniaxial deformation. In the course of processing, the grains are oriented and stretched along the deformation axis, with consequent decrease in the width. That is why the elongation ratio has been gradually reduced from 0.65 to 0.12 while the classical drawing.

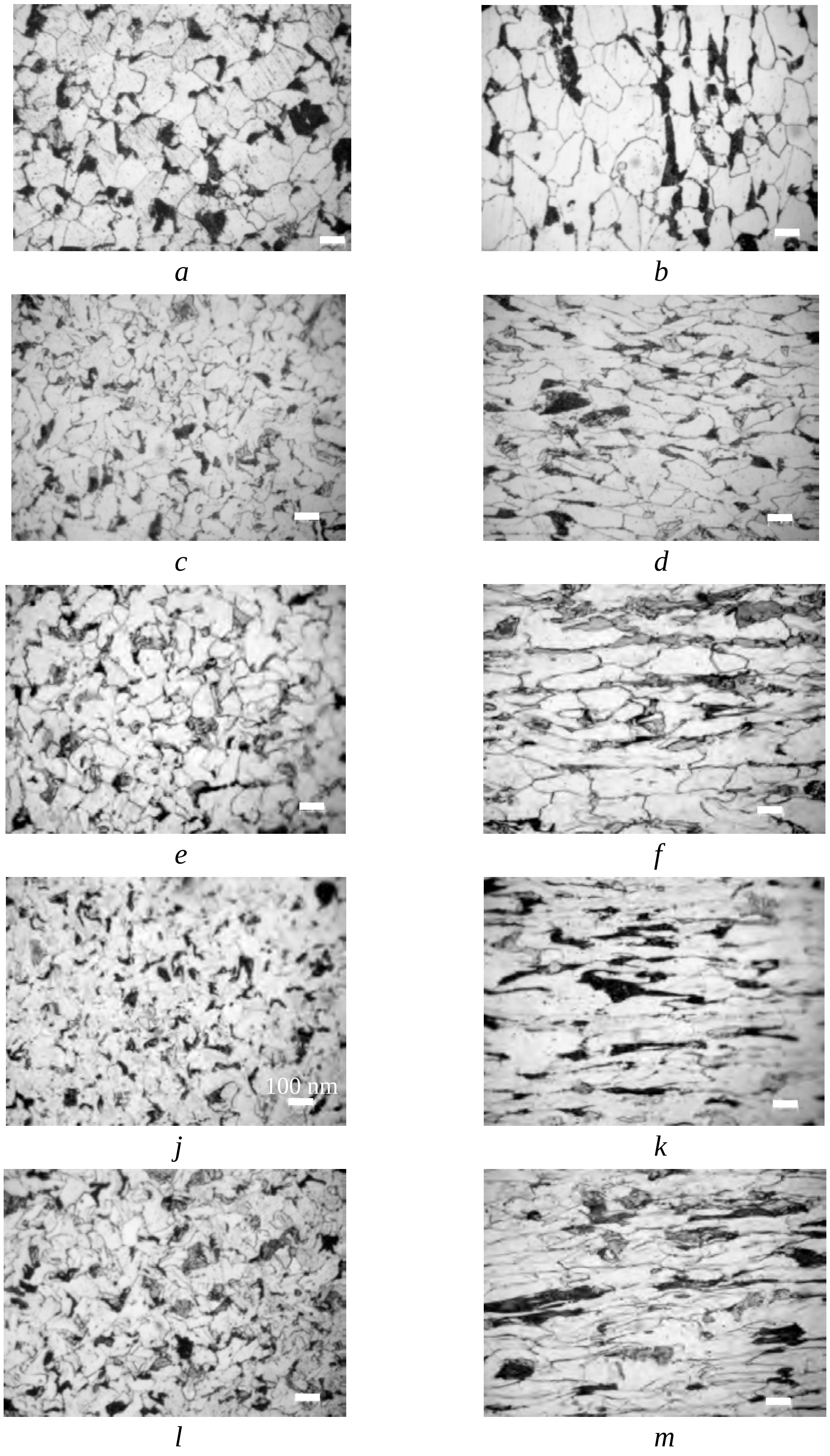


Fig. 1. Microstructure of low-carbon steel wire after drawing: as-received state (*a*, *b*), ∅6.15 mm; classical technology (*c*, *d*, *j*, *k*); experimental technology (*e*, *f*, *l*, *m*): *c*, *d*, *e*, *f* – ∅5.0 mm; *j*, *k*, *l*, *m* – ∅3.9 mm; *a*, *c*, *e*, *j*, *l* – cross; *b*, *d*, *f*, *k*, *m* – longitudinal section; magnification ×1000. Scale bar 20 μm except *j*

A certain non-linar decrease in the elongation ratio is also observed after the experimental technology. The increase up to 0.72 characterizes the sample ∅3.9 compared with 0.47 for the ∅5.0. This effect is related to the application of a die with shear that forces a change in the metal flow.

The analysis with the use of the optical microscopy allowed fixing the following principal structure features.

1. When drawing by the classical technology, an increase of the deformation degree is associated with a grain size reduction according to the Taylor–Polani principle (Table 4). It has been established that the classical technology results in an increase in the grain size in the longitudinal section and its reduction in the cross-section. Contrary to the classical drawing, the modification of the grain size in the course of the experimental drawing is non-monotonic and the processes of grain fragmentation are periodically substituted with a grain size increase. In the longitudinal section, the experimental technology generates a decrease in the grain size, not an increase (compare 9.02 and 4.53 μm). This effect can be explained by both the changes in the metal flow within the dies with shear and a possible progress in the competing processes of fragmentation and dynamical polygonization/re-crystallization.

Table 4

Grain size after drawing of the low-carbon steel wire

Diameter, mm	Grain size, μm			
	Drawing technology			
	classical		experimental	
	along the drawing axis	across the drawing axis	along the drawing axis	across the drawing axis
5.0	8.70	5.72	8.78	4.14
3.9	9.02	4.02	4.53	3.28

The dilemma can be solved at the rate of utilization of other experimental technologies, for instance, structure analysis by a scanning electron microscope. The data of the EBSD analysis listed below detail the conception of the structure formation.

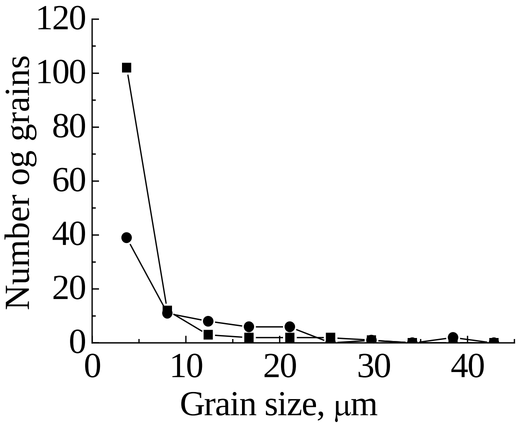
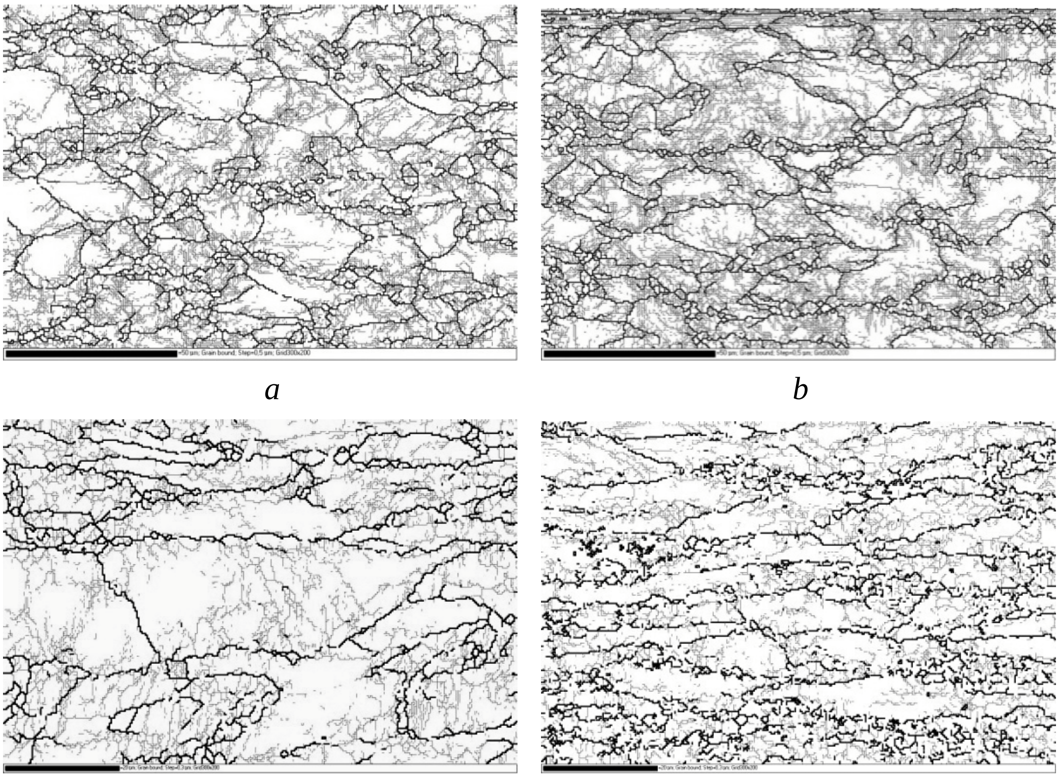


Fig. 2. Grain size histograms in the samples of the low-carbon steel wire ∅3.9 mm

2. The curves illustrating the grain size distribution are presented in the section along the drawing axis (Fig. 2). It is well seen that the experimental drawing technology results in a substantial increase of the fraction of small grains (less of 4 μm) and a decrease in the fraction of coarse grains. For instance, if the classical drawing technology has been applied, the presence

of the grains larger than 44 μm is registered. After the experimental drawing, the grains larger of 32 μm are not fixed.

The tests have demonstrated that the state of the grain boundaries is similar at low degree of deformation for both technologies: relatively coarse grains surrounded by HABs are observed (Fig. 3,*a* and *b*). Inside these grains a fine structure has been formed in the shape of pileup of dislocations, cells and LABs (subboundaries). However the total density of the LABs after the experimental drawing is higher than after the drawing by the classical scheme.



a *b*

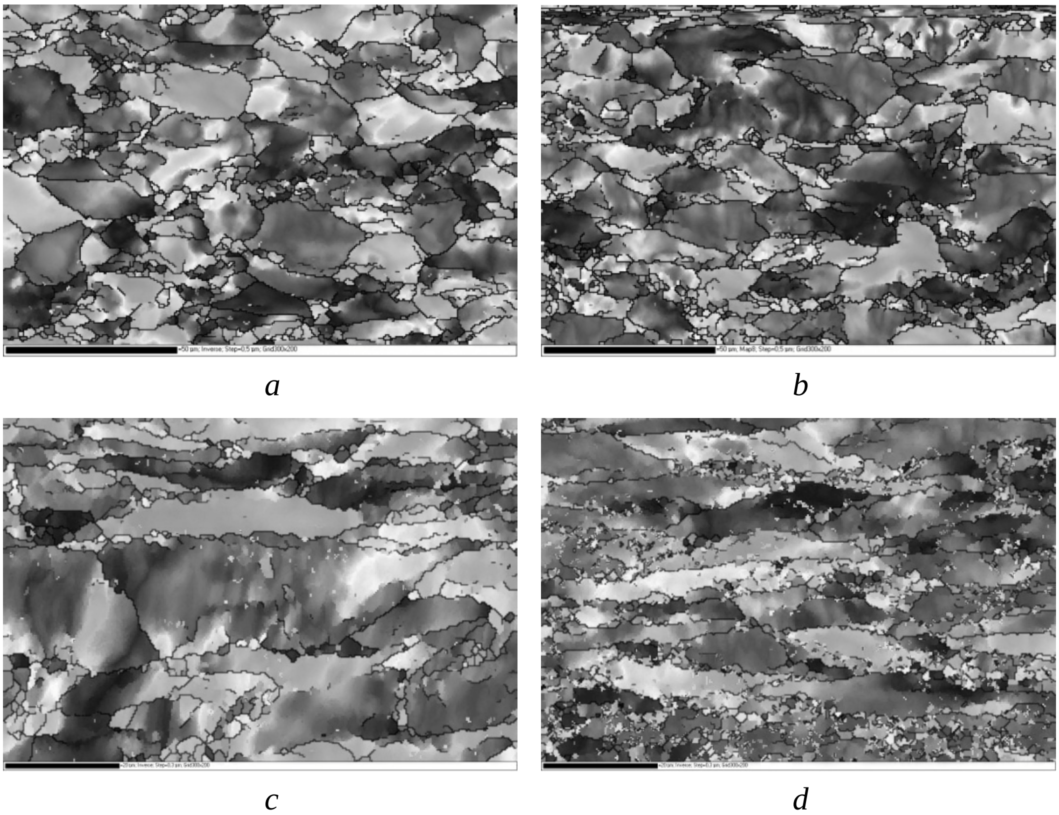
c *d*

Fig. 3. Maps of the grain boundaries of low-carbon steel wire samples (longitudinal section), obtained by the classical technique (*a*, *c*) and by the experimental technique (*b*, *d*): *a*, *b* – ∅5.0 mm scale bar 50 μm; *c*, *d* – ∅3.9 mm scale bar 20 μm. HABs and LABs are marked black and gray, respectively

At the same time, when the degree of deformation increases, the character of the formed boundaries changes. After the classical drawing, the dislocations are arranged in the sub-boundaries against the background of the general grain reduction. Due to this fact, areas relatively free of defects appear within the grains. After the experimental drawing, the fraction of the HABs grows substantially both on account of very small fragmented grains less than 3 μm in size and at the rate of relatively large grains that increase the grain-boundary angle in the course of deformation. Some segments of deformation-induced subboundaries within grains accumulated misorientation exceeding 10° thus transforming into HABs (several examples are arrowed in Fig. 3). This perhaps indicates a development of *dynamical* recrystallization, that is not expected for this material at ambient temperature. As follows from the comparison of Figs 3,*c* and 3,*d*, the LAB-to-HAB transformation was more pronounced in the drawn with shear material than that in the material processed by classical technology. This presumably explains faster grain refinement and thus higher strength.

Besides, electron backscatter diffraction allowed the analysis of grains of different types: deformed, substructural, recrystalized. The grains are classified as follows: 1 – a criterion of the grain selection is established (the misorientation angle is above 10°, being associated with the HABs); 2 – the threshold value of misorientation is selected that corresponds to the standard instrumental error (2°); 3 – if the average value of misorientation of the points within a grain exceeds the selected threshold value, the grain is identified as a deformed one; 4 – if the grain is composed of subgrains and the average value of misorientation within the subgrains does not exceed the threshold value but there is an excess between the subrains, the grain is a substructural one; 5 – if the average misorientation within a grain does not exceed the selected threshold value, the grain is a recrystallized one.

In Figs. 4 and 5 the maps of crystallographic orientations and the grain types after different kinds of drawing are presented. The maps confirm the idea that the formed small grains (less of 3 μm) are recrystallized. A possible mechanism of formation of this type of grains is fragmentation of coarse grains to the grain size

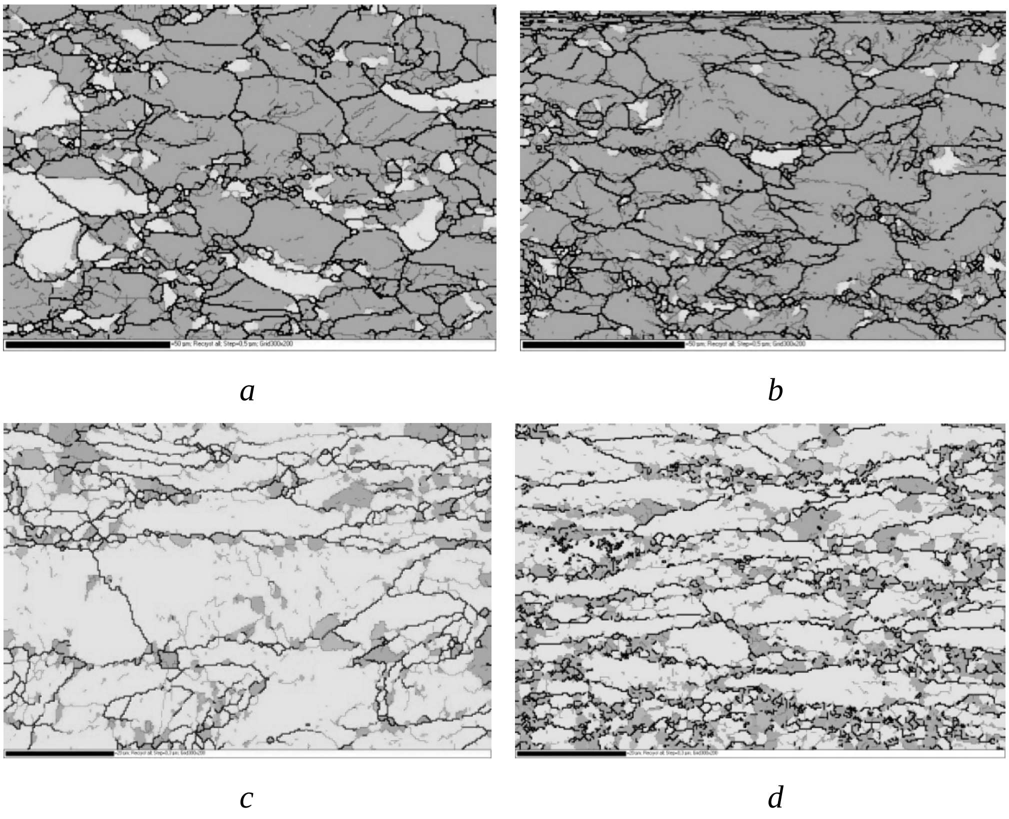

a *b*

c *d*

Fig. 4. Maps of the crystallographic orientations of low-carbon steel wire samples (longitudinal section), obtained by the classical technique (*a*, *c*) and by the experimental technique (*b, d*): *a, b* – ∅5.0 mm scale bar 50 μm; *c, d* – ∅3.9 mm scale bar 20 μm.

down to 3 μm. This type of grains should demonstrate structure imperfection due to a large amount of defects and related noticeable lattice distortion. However it has been established that the change of crystallographic orientations within the grains is stepwise, not smooth due to the bending of crystallographic planes (Fig. 4,*d*). In other words, the grains are structurally perfect, the lattice inside the small grains is not distorted. This fact characterizes the case of formation of deformed structure due to the grain boundary sliding (GBS) or GBS combined with dynamical recrystallization. A consequence of these processes is the change of the character of the grain boundaries from smooth to serrated and formation of incompleted HABs.

The data presented in Fig. 5,*c* and *d* count in favor of the last statement. After the drawing with the experimental technology, the amount of the recrystalized grains increases from 2.5 to 4.8% in comparison with the classical drawing technology. Besides, an increase in the fraction of the deformed grains is enhanced from 12.5 to 22%. The presence of recrystalized grains is an evidence of occurred mechanically activated dynamical recrystalization.



a *b*

c *d*

Fig. 5. Maps of the grain types in the samples of low-carbon steel wire samples (longitudinal section), obtained by the classical technique (*a*, *c*) and by the experimental technique (*b*, *d*): *a*, *b* – ∅5.0 mm scale bar 50 μm; *c, d* – ∅3.9 mm scale bar 20 μm. The deformed, substructural and re-crystallized grains are marked middle gray, light gray and gray, respectively

Thus, at high degree of deformation, the structure formed by the classical and experimental drawing technologies differs drastically. After the experimental processing, the grain is reduced more substantially. The experimental technology results in a noticeable increase in the fraction of small grains (less than 3 μm in size) and a reduction in the fraction of large grains. A large amount of small grains with HABs is registered on the boundary.

The study of unetched specimens by optical metallography demonstrated that pores are formed when wire passes the first die with shear. These pores are healed to a large degree in the course of the subsequent drawing. This fact is confirmed by the data about the density (Fig. 6). The utilization of the second die with shear results in a process of density recovery up to the wire of small diameter ∅1.55. On the whole, the density of the experimental drawn samples is substantially larger that provides high drawing ability without annealing.

The comparative analysis of the hardness tests has demonstrated that the hardness increases with decreasing the sample diameter after the classical and the experimental drawing as well (Fig. 7). The difference is that the hardness grows linearly after the classical drawing and the increase after the experimental drawing is stepwise. The linear increase of the hardness after the classical drawing is related to a decrease in the grain size and formed enhanced density of LABs and dislocations.

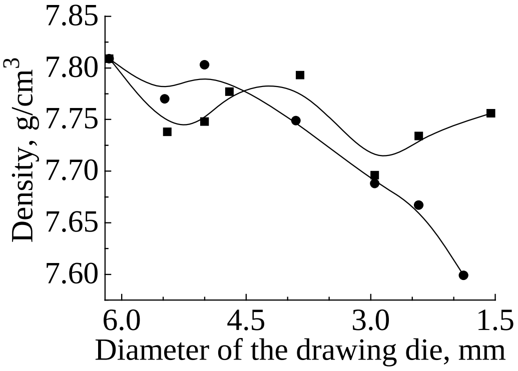
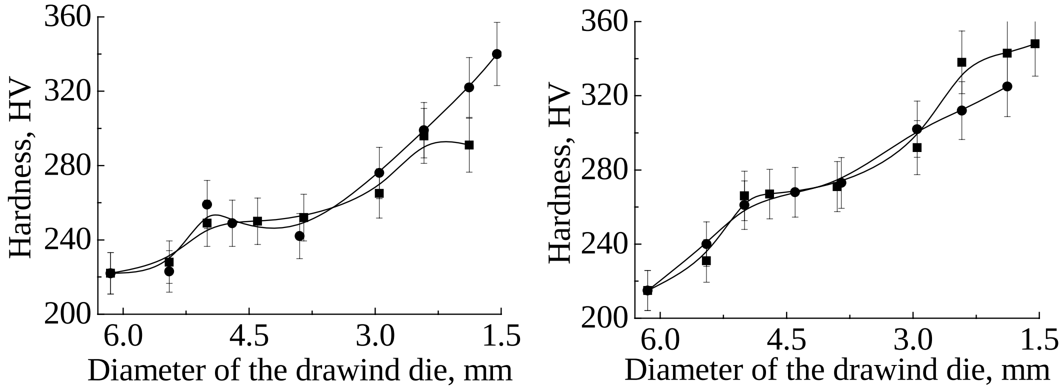


Fig. 6. Density of the wire from the low-carbon steel produced by different technologies



a

b

Fig. 7. Hardness of the wire from low-carbon steel produced by the classical (●) and the experimental (■) technologies: *a* – cross-section, *b* – longitudinal section

When using the experimental technology, an important specific feature is the fact that the hardness exceeds on about 300 HV than in classical drawing both in the longitudinal and the transversal diameter (starting from ∅2.42). This behavior of curves confirms certain progress in the processes that differs from occurring while the classical drawing. An increase in hardness after the experimental drawing is associated with an appearance of a large amount of small grains with high-angle boundaries. From author's opinions, this kind of the structure modification is a consequence of the development of dynamical recrystallization against the background of the persisting grain fragmentation during drawing. The nuclei of new grains appear and start growing at the boundaries of the deformed primary grains. When the size of new grains increases gradually, they become involved into the deformation process. As a result, their uniaxial shape becomes elongated and the lattice becomes distorted. Thus, the progressing dynamical recrystallization is associated with an increment of the hardness, not a decrease.

Stepwise increase in the hardness correlates with the enhanced density that can be explained by healing of pores and cavities. An explanation could be in change of the metal flow direction when the wire passes the conventional dies after a die with shear.

Conclusions

Feasibility of drawing with shear for production of low-carbon steel wire was examined. As compared to conventional drawing technology, the new approach was shown to enhanced grain refinement, reduction of the structure anisotropy and thus imparted additional material strengthening. All of these benefits were attributed to a specific «twist» character of material flow.

1. At high degree of deformation, the structure formed by classical and experimental drawing differs drastically: the grain reduction is stronger in the course of experimental drawing processing. The experimental drawing technology results in an extensive increase in the fraction of small grains (less than 3 μm in size) and a decrease in the fraction of large grains. A large amount of small grains with HABs is registered on the boundary.

2. Formation of this kind of grains is explained by the progress in competing processes of large grain fragmentation and dynamical recrystallization. The result is the change of the character of the grain boundaries from smooth to serrated ones and formation of incompleted HABs. Besides, it has been demonstrated that a certain part of small grains provides grain boundary sliding.

3. A specific feature of the experimental technology is a reduction of the structure anisotropy. This effect is related to the application of dies with shear that make the metal flow to change the direction.

4. When the wire passes the first shear die, pores are formed. The utilization of the second shear die results in progressing recovery of the samples density up to the level of a small-diameter wire ∅1.55. This fact is associated with the change of the metal flow when the wire passes the conventional dies after the die with shear.

The work was done with the support of the economic contracts project #13-13 DonIPE NAS of Ukraine «Wire drawing technology to improve ductility without the use of the heat treatment».

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ВОЛОЧЕНИЕ СО СДВИГОМ – ЭФФЕКТИВНЫЙ МЕТОД УПРАВЛЕНИЯ СТРУКТУРОЙ И СВОЙСТВАМИ МАЛОУГЛЕРОДИСТОЙ СТАЛИ

Разработана технология волочения со сдвигом для изготовления проволоки из малоуглеродистой стали без отжига. Установлено, что особенностью предлагаемой технологии являются снижение анизотропии структуры и увеличение ресурса пластичности. Этот эффект связан со сдвиговой деформацией, которая вызывает изменение направления течения металла.

Ключевые слова: волочение со сдвигом, структура, свойства, интенсивная пластическая деформация.