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**UDC 621.77.014**

DOI: 10.17580/cisisr.2018.02.08

# EVOLUTION OF CEMENTITE IN PEARLITE CARBON STEEL WIRE AT COMBINED DEFORMATIONAL PROCESSING*

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*Key words:*

Keywords: carbon steel wire; cementite; pearlite; combined deformational processing; drawing; bending; torsion.

ABSTRACT

Implementation of combined methods of deformational processing is on the cutting-edge of downstream steel manufacturing. The effect of plastic deformation on metals is the irreversible particular changes in microstructure. To develop new technological processes of metal ware manufacturing it is necessary to study the microstructure changing features in steel in order to predict its properties. Carbon steel wire with pearlite structure is used for a wide range of engineering components. Carbon steel wire was plastically deformed by drawing in combination with bending and torsion. Such combination resulted in characteristic changing of cementite plates. The main objective of the paper is to correlate cementite evolution of carbon steel wire after combined deformational processing by drawing with bending and torsion with its mechanical properties. The construction of the used laboratory setup consisted of two drawing dies and four-rolls system which makes it possible to change the deformation degree during drawing, bending by the use of rolls with different diameters as well as torsion deformation in wide range. Scanning electron microscopy and tensile test were used for analysis of processed carbon steel wire. It was observed that after combined deformational processing cementite lamellas were destroyed. After combination of drawing with bending, cementite lamellas became curve especially when in the four-rolls system the rolls with smaller diameter were installed. By the combination of drawing with bending and torsion, the cementite lamellas changed in the same manner as without torsion deformation, but boundaries between pearlite colonies could not be identified with smaller diameter of rolls. Because combined deformation schemes during combination of different kinds of deformation was rather complicated, they had different impact on strength and ductile properties of the processed pearlitic wire.

## 1. Introduction

Pearlitic steel wire has a wide range of application. It is used as semi-product in downstream steel manufacturing for cables, meshes, cord, etc. and as a finished product in electronic devices, medical equipment, watches, etc. [1]. Pearlite structure consists of cementite lamellae with low extent of ferrite which are very sensitive to any kind of deformational processing. This peculiarity of pearlite change on each stage of wire production, influences the behavior of eutectoid steel at further stages of downstream production [2–4].

The basic operation for steel wire production is drawing. The main strain at drawing is the tensile deformation along the wire axis. This feature of the applied strain affects the changes in microstructure of the processed wire when steel grains elongate along the drawing direction. Such kind of microstructure is denoted as texture which affects to high extent on mechanical properties of drawn pearlitic steel wire. Much research has focused on texture formation after drawing and its effect on mechanical properties of pearlitic wire [5–10]. It was proved

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* Authors appreciate PhD Alexandr Gulin (Nosov Magnitogorsk state technical university) for conducting tensile tests of the processed carbon steel wire and interpreting the experimental results.

experimentally that drawing induces elongation of ferrite grains with the development of <110> fiber texture. The cementite lamellae also have a tendency to reorient themselves along the wire axis with increasing strain. The relationship between structure evolution and strength of pearlite steel is presented in [6]. Authors explain the increase of pearlitic steel wire strength both by accumulation of high density dislocation in ferrite phase forming in cementite lamellae and the amorphous phase forming in cementite lamellae. The concept of pearlite block which is defined as an area which constant crystallographic orientation of ferrite, was proposed in order to explain the level of pearlitic wire ductile properties [7]. It was revealed that pearlite block acts as a unit of slip and fracture of pearlite steels. Authors report that refinement of austenite grains which is effective in improving the ductility of pearlite steels, is due to the resulting refinement of pearlite blocks. Increase in ductility was found to be due to the increase in ductile mode area at the fractured surface.

Due to the specific set of strength and ductile properties the pearlitic steel wire has been attracting interest in different fields such as civil engineering [11], tyre manufacturing [12,13], concrete reinforcement [14] etc.

It is generally accepted that peculiarities of cementite lamellae behavior under deformational conditions play a significant role in pearlitic wire properties formation. Numerous investigations were conducted in order to determine mechanisms of cementite decomposition in drawn pearlite steel wire [15–20]. As a result of these studies, the complete dissolution of cementite lamellae was observed in specimens deformed with large strains at high strain rates. Cementite lamellae in deformed pearlite exhibited inhomogeneous slip, smooth thinning or necking, fragmentation and cleavage fracture. Dissolution of cementite was also observed in cold rolling [21].

Decomposition behavior of cementite in high carbon steel wires during drawing and aging was investigated in [22]. Authors explain the mechanisms of cementite decomposition at high deformation degree as follows. When the wire is drawn, carbon atoms in ferrite move within the dislocation strain fields, and the carbon concentration around dislocations is locally lowered. On the other hand, the carbon concentration in the matrix should be in equilibrium with the cementite. Accordingly, the diffusion of carbon atoms into the depleted region around dislocations leads to a general decrease of the carbon concentration, and cementite then dissolves tending to maintain the local equilibrium of carbon content in the matrix. This theoretical base can be used to assign the technological regimes of pearlitic wire manufacturing in order to obtain the final product with definite level of mechanical properties.

On the other hand, analysis of cementite decomposition is important for the following reasons. At present time, this kind of microstructure can be considered as nanostructure because of the small spacing between cementite lamellae which is the main factor affecting the level of pearlitic wire mechanical properties [23-27]. It was proposed [24] to subdivide the lamellar structure into two distinct different types depending on interlamellae spacing and dislocation density. This approach makes it possible to estimate the contribution of different structural parameters to the mechanism of the total flow stress. Such complicated behavior of cementite lamellae under deformation became the background for quantitative investigation of microstructure changes [28, 29].

One of the tendencies in downstream steel manufacturing is the implementation of combined and integrated processes in the industrial scale. Combined and integrated technologies are considered to be materials and energy saving processes. Combination of different operations shorten the technological chain and simplify the manufacturing process [30–33]. This approach is very perspective for wire manufacturing because drawing process has many limitations and drawbacks. From this point of view combined deformational processing is the way to achieve much higher level of microstructure refinement compared to the conventional wire drawing process [34, 35].

However, scarce attention is paid to the investigation of the features of microstructure formation in drawing process combined with other methods of plastic deformation. The aim of this paper is to study changes in cementite in pearlitic wire after different kinds of combined deformational processing by drawing with bending and torsion. Several results have already been presented in [36–38]. The approach used in this study makes it possible to illustrate the correlation between cementite lamellae evolution at different kinds of combined deformational processing with wire mechanical properties.

## 2. Materials and Methods

Chemical composition of medium carbon steel wire with 3.05 mm in diameter in as-received state chosen for investigation is presented in **Table 1**.

Wire processing varying combination of different kinds of plastic deformation was performed on the laboratory setup presented in figure 1, a. Two conical dies are installed in the frame. Between them the four rolls system is arranged. Carbon steel wire is exposed both tensile and compression plastic deformation while going through dies and bending deformation is arranged by rolls system. The particular feature of this setup is that continuously moving wire can be processed by different kinds of deformation simultaneously or separately.

Four rolls system has the individual engine which enables its rotation at different torsion speed. For the ex-

Table 1. **Chemical composition of medium carbon steel wire**

| Element | C | Si | Mn | Al | Ni | Cr | Cu | P | S | N |
|---|---|---|---|---|---|---|---|---|---|---|
| Concentration (wt %) | 0.47–0.53 | 0.17–0.37 | 0,50–0,80 | 0.02 | till 0.3 | till 0.25 | till 0.3 | till 0.02 | till 0.03 | till 0.008 |

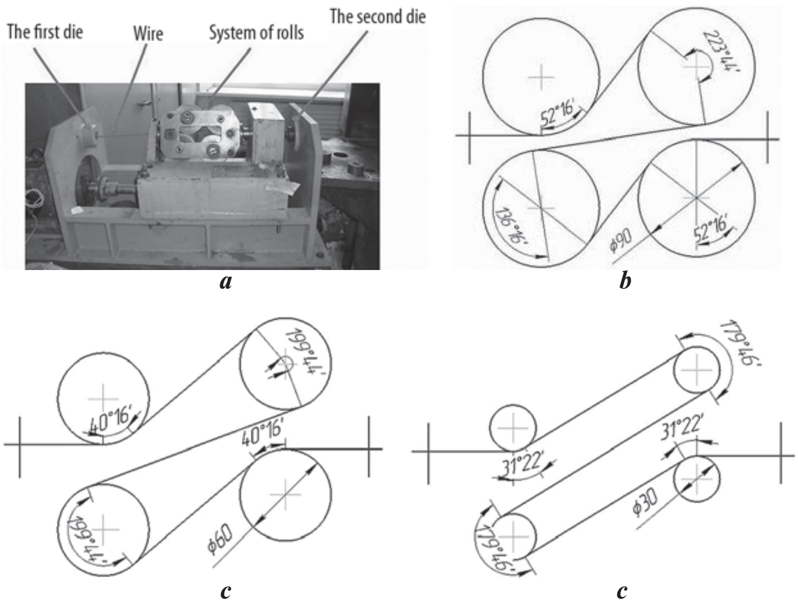

**Fig. 1. Laboratory setup for combination of drawing with bending and twisting. Bending deformation changing during combined deformation processing with different rolls diameter in four-rolls system:**
*b* — rolls with 90 mm in diameter; *c* — rolls with 60 mm in diameter; *d* — rolls with 30 mm in diameter

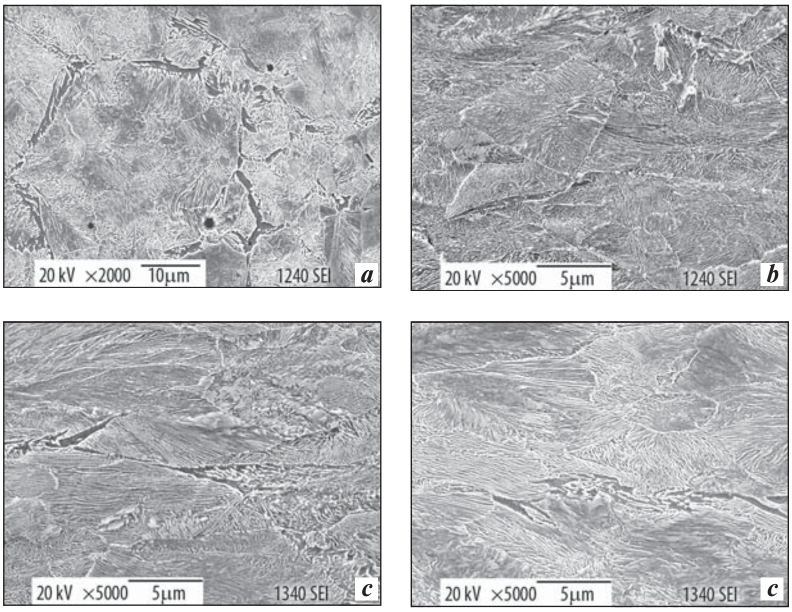

**Fig. 2. Microstructure of carbon steel wire 0.5% C in as-received state (*a*); after drawing with total deformation degree:**
*b* — 18.70%; *c* — 26.77% and *d* — 35.47%

periments total deformation degree in the dies was chosen 18.70%, 26.77% and 35.47%. Using rolls with 90 mm, 60 mm and 30 mm in diameter it was possible to vary deformation by bending. In accordance with the schemes (**Fig. 1, *b–d***) the angles of rollers coverage were 52 and 223° for rolls with 90 mm in diameter, 40 and 199° for rolls with 60 mm in diameter, 31 and 179° for rolls 30 mm with in diameter. The rate of four-rolls system torsion was 150 RPM (rotation per minute).

Scanning electron-microscope analysis of the wire was done on the electron microscope JEOL JSM-6490 LV with accelerating voltage 30 kW in modes of secondary and temporary reflected electrons in conditions of Nano Steel Research Studies Institute of Nosov Magnitogorsk State Technical University. Samples for metallographic examination were prepared from the deformed wire by standard technique by polishing and etching. Microstructure of medium carbon steel wire after different kinds of deformational processing was observed in longitudinal cross section.

Mechanical properties of the processed carbon steel wire were studied by standard tensile test in accordance with ISO 6892-1:2009(en) «Metallic materials – Tensile testing – Part 1: Method of test at room temperature». Tensile tests were performed on samples obtained after different rotation rate of the four-rolls system.

## 3. Results and Discussion

In as-received state microstructure of medium carbon steel wire is typical microstructure of 0.5%C steel (**Fig. 2, *a***). It consists of pearlite colonies with low content of ferrite randomly located around pearlite colonies. Volume part of pearlite is approximately equal to 60%. Cementite is not fragmentized.

After drawing both pearlite colonies and structurally free ferrite grains elongate along the main line of tensile deformation (Fig. 2, *b*). This is proved both by the metallographic texture formation and by the appearance of plastic deformation rotation mode especially when the deformation degree increase. Moreover, at high deformation degree cementite lamellas start to fragment (Fig.2 *d*).

In **Fig. 3** cementite evolution after combined deformational processing by drawing with bending is presented.

In all cases of combined deformational processing the cementite lamellas are fragmented. The dispersion of cementite is different depending on the deformation intensity. Combination of drawing with bending causes the increasing of cementite anisotropy when the rolls diameter decrease. The length of the majority of cementite lamellas can be compared with the dimension of the whole pearlite colony. The interlamellae spacing in cementite decreases at combination of drawing with bending on rolls with 30 mm in diameter. In this case microstructure is more uniform as compared with other variants of rolls diameter

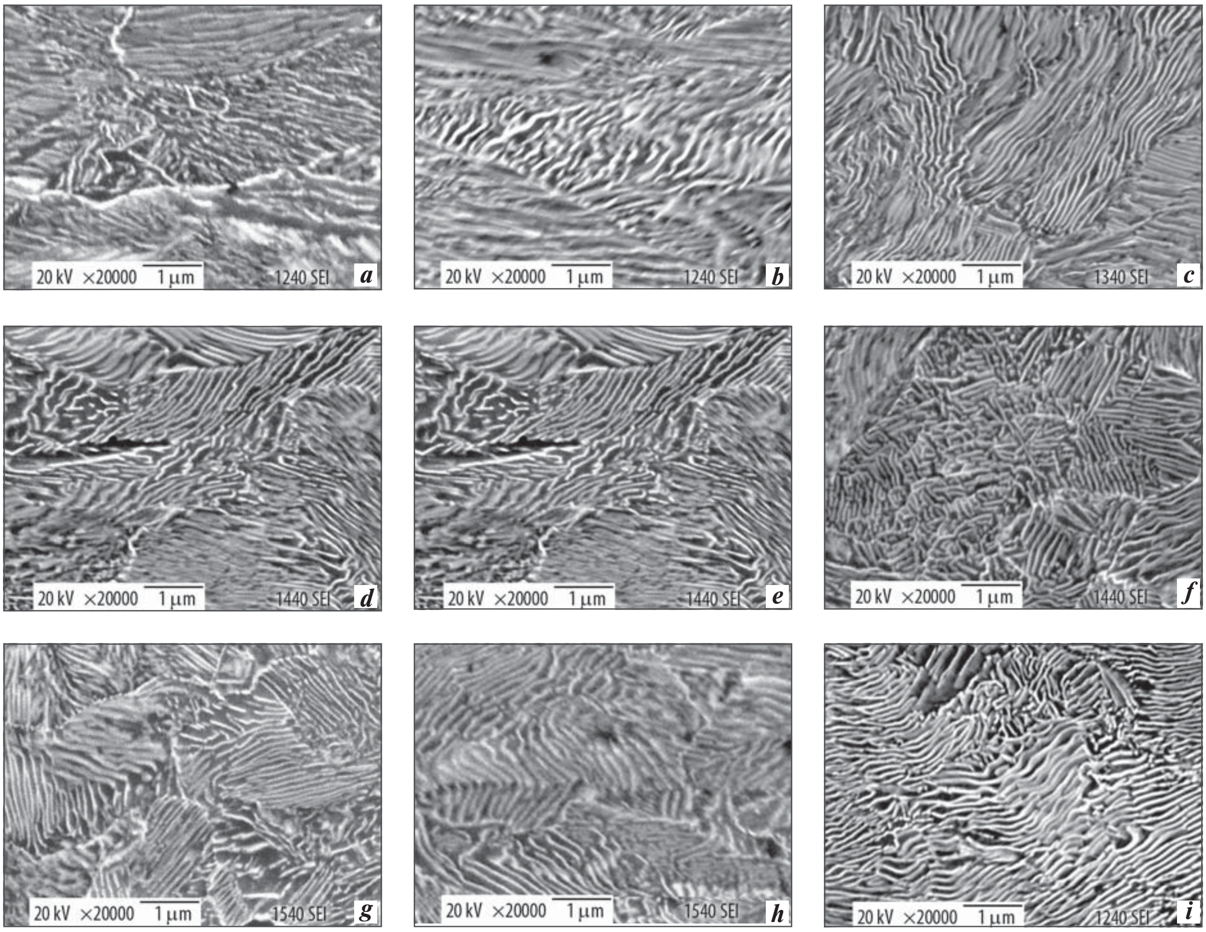

**Fig. 3. Cementite evolution at combined deformational processing of pearlite carbon steel wire by drawing with bending in four-rolls system:**
*a–c* — rolls with 30 mm in diameter; *d–f* — rolls with 60 mm in diameter; *g–i* — rolls with 90 mm in diameter; *a*, *d* and *g* — total deformation degree at drawing 18.70%; *b*, *e* and *h* — total deformation degree at drawing 26.77%; *c*, *f* and *i* — total deformation degree at drawing 35.47%

combination. Cementite lamellas become more curved when rolls with smaller diameter were used. Supplement of torsion deformation by rotation of four-rolls system with 150 RPM to combined deformational processing results in more intensive fragmentation of cementite lamellas (**Fig. 4**).

After combination of drawing with bending and torsion, the cementite lamellas change is practically the same as without torsion deformation but the microstructure texture is more evident. When torsion deformation is applied, the extension of cementite lamellae fragmentation is higher and microstructure results more dispersed. Boundaries between pearlite colonies can not be identified when smaller diameter of rolls are used. Imposing torsion deformation causes curvature of cementite lamellas.

Microstructure changes after combined deformational processing by drawing with bending and torsion affect on the carbon steel wire mechanical properties (**Fig. 5**).

Combination of different kinds of deformation has different impact on mechanical properties of the processed medium carbon steel wire. In general, the level of tensile strength of the processed wire can be compared with same level of the wire after drawing. But combination of drawing with bending and with bending and torsion has its peculiar impact on strength and ductility of the processed wire. Drawing with deformation degrees of 18.7% and 35.47% and the combination of drawing with bending does not influence significantly on tensile strength. An appreciable decrease of tensile strength was observed on samples drawn with deformation degree of 26.77%. Combination of drawing with bending and torsion has the same impact on the tensile strength level of the processed wire. Change of yield strength level depends on bending deformation. Combination of drawing with bending on rolls with 30 mm and 60 mm in diameter does not result in such significant extent as it is observed using rolls with 90 mm in diameter. Combination of drawing with bending and torsion is more effective for improvement of yield strength level using rolls with 90 mm in diameter.

These peculiarities of carbon steel wire mechanical properties after different variants of combination of deformational processing matches well with cementite evolution when cementite lamellas change their shape, regularity, level of dispersion in a wide range. Reduction

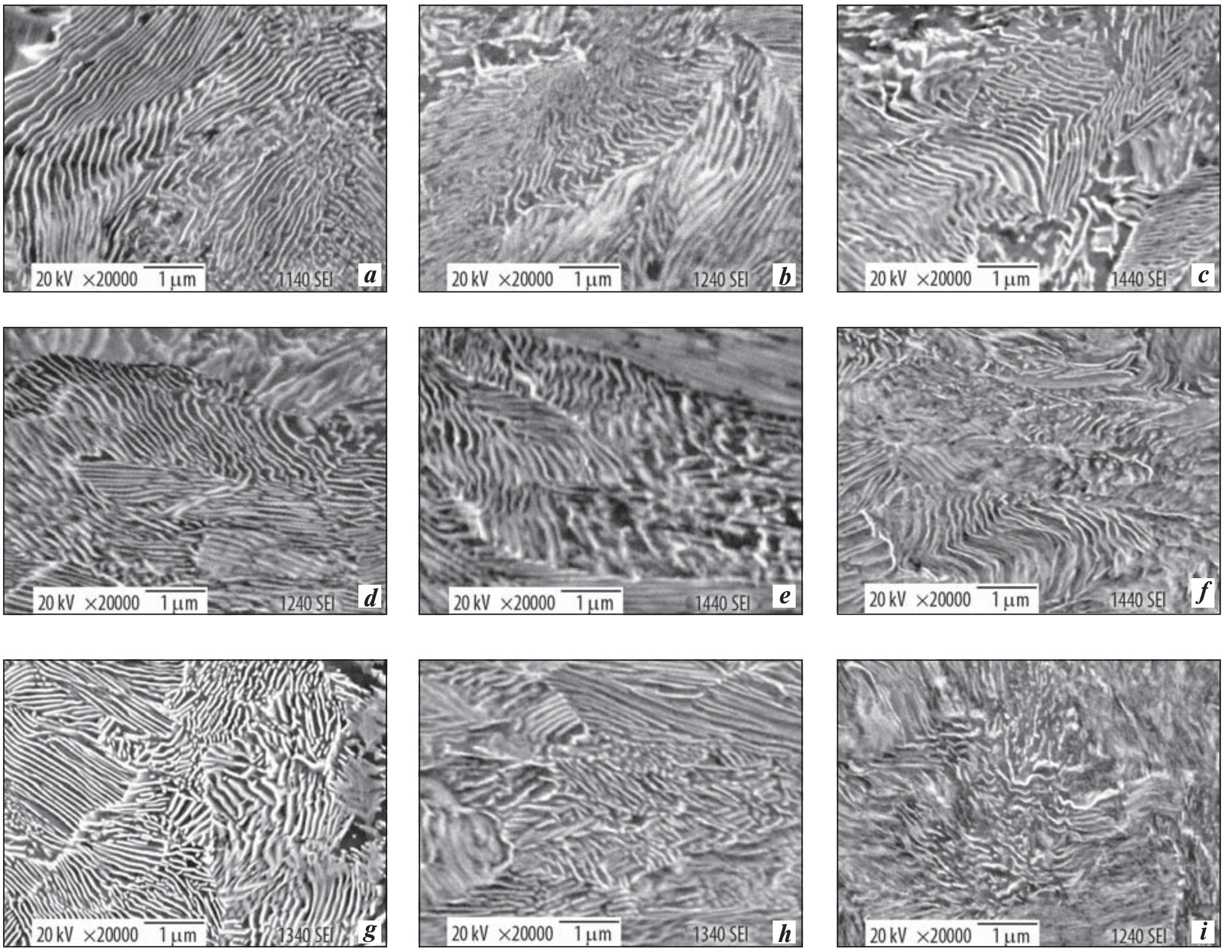

**Fig. 4. Cementite evolution at combined deformational processing of pearlite carbon steel wire by drawing with bending and torsion at 150 RPM in four-rolls system:**
*a–c* — rolls with 30 mm in diameter; *d–f* — rolls with 60 mm in diameter; *g–i* — rolls with 90 mm in diameter; *a*, *d* and *g* — total deformation degree at drawing 18.70%; *b*, *e* and *h* — total deformation degree at drawing 26.77%; *c*, *f* and *i* — total deformation degree at drawing 35.47%

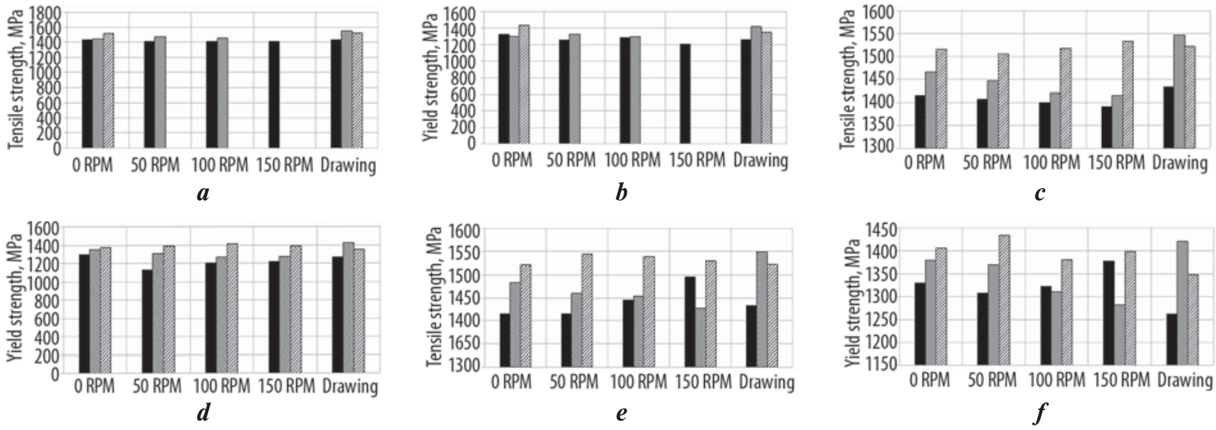

**Fig. 5. Mechanical properties of pearlite steel wire after combined deformational processing by drawing with bending and torsion:**
*a* and *b* — rolls with 30 mm in diameter; *c* and *d* —rolls with 60 mm in diameter; *e* and *f* — rolls with 90 mm in diameter; deformation degree at drawing,%: ■ — 18.7; ▩ – 26.77; ▨ — 35,47

ability of strain hardening of carbon steel wire after combined deformational processing can be explained by fewer ferrite component, which is the area of plastic shear strain accumulation and fragmentation.

## 4. Conclusions

Combined deformational processing by drawing with bending and torsion has been conducted on continuously moving wire in order to estimate cementite evolution. It was found that such combination of different kinds of deformation leads to forming a curved microstructure of cementite plates. Cementite plates fragmentation was observed and this produced a more uniform microstructure if compared with the as-received state. Such peculiarities of cementite evolution affect the level of pearlite steel wire mechanical properties. Because combined deformation scheme is rather complicated, it has different impact on strength and ductile properties of the processed pearlitic carbon steel wire. In particular, using large rolls diameters the yield strength of the wire is improved.

From practical point of view it can be find such combination of deformational processing which makes it possible to get different level of strength or ductility or their set which is necessary for pearlite steel wire in accordance with its usefulness.

***Aknowledgment. The reported study was funded by RFBR according to the research project №18-58-45008 IND_a.***

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**UDC 669.194.2** DOI: 10.17580/cisisr.2018.02.09

# UNDERSTANDING THE EFFECT OF DEOXIDATION REGIME ON THE FORMATION AND ARRANGEMENT OF SULPHIDE INCLUSIONS AND ON MECHANICAL PROPERTIES IN STEEL

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*Key words:*
Non-metallic inclusions, deoxidation, aluminium, silicocalcium, oxidation level, grain boundary, steel, mechanical properties, sulphides.

ABSTRACT

This paper looks at the effect produced by oxygen on oxide, oxysulphide and sulphide inclusions and how they form in medium-carbon and low-alloy steels. The results of a laboratory study that looked at specimens made of steel 45, revealed a negative role of aluminium used as a deoxidizer, as it causes the sulphide inclusions arrange themselves at grain boundaries. In 38KhN3MFA steel specimens deoxidized with silicocalcium, the sulphide inclusions have better arrangement as they are located in the grain, due to the doping effect of the deoxidizer. The authors analyze how the level of oxidation (vacuum degassing) in and the type (basic or acidic) of the 38KhN3MFA steel can affect the mechanical properties of forgings for power engineering application.

## Introduction

Modern steel making technology enables to produce high-quality steel products due to the application of secondary metallurgy processes [1].

At the same time, some research papers [2, 3] point out that the strive for ultralow concentrations of impurities in the melt does not always lead to enhanced performance of metal (and in some cases, this can even result in performance degradation). This can be attributed to the thermodynamics and kinetics behind the formation and growth of non-metallic inclusions when one of the reagents is lacking in the process. The mechanism behind this phenomenon is yet to be investigated. Researchers still need to understand how non-metallic inclusions form, arrange themselves and behave in a strong deoxidation environment or in vacuum.

What makes the need to thoroughly investigate how inclusions affect the structure and properties of steel ever so relevant is increasingly stricter requirements to the quality of parts produced from large ingots, and a general trend to produce heavier ingots. The latter leads to a greater unevenness in the distribution of inclusions in the metal and a poorer uniformity of its properties [4–6].

One of the main targets in improving the steel quality is to minimize the concentration of sulphur as the most harmful of the impurities. What gives relevance to this problem is the way sulphide inclusions form and behave during processing. The workpieces are not strong enough and can be easily deformed and longitudinally stretched during rolling, which affects the uniformity of properties