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Microstructure and mechanical properties of steel rods after controlled deformation

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ABSTRACT

Purpose: : The goal of the study was to determine the influence of controlled deformation by RCS (repetitive corrugation and straightening) process on the structure and mechanical properties of S235JR steel. The influence of process parameters on the above properties was investigated.

Design/methodology/approach: This study was aimed to investigate structure and mechanical properties of hot rolled rods of S235JR steel, subjected to intensive plastic deformation using the RCS (repetitive corrugation and straightening) method.

Findings: Microstructure of the examined steel of S235JR grade is typical for hot rolled conditions. It was found out that in the initial material the perlite lamellae grew mainly in the direction perpendicular to the axis of the rod, i.e. in the direction of the highest rate of heat dissipation. The perlite lamellae in the rods after bending presented more random arrangement, and some of them were crushed. The process of bending should, therefore have a positive influence (decrease) on the anisotropy of mechanical (plastic) properties.

Practical implications: Investigation results can be easily applied into industrial technology.

Originality/value: This paper presents the results of study of the structure and mechanical properties S235JR steel after controlled deformation.

Keywords: Steel rods; Microstructure; Metal working; Mechanical properties; Infrared examination

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MATERIALS

1. Introduction

There are many worldwide known techniques of severe plastic deformation (SPD) which lead to production of controlled microstructure-ultrafine or nanocrystalline-in metallic materials. Currently, the SPD techniques are becoming upgraded from research scale to industrial scale and commercial applications [1-7]. More and more attention is paid to development of equipment for continuous production of ultrafine crystalline microstructure in metals and alloys, as well as to economics and reliability of such equipment and processes. When applied to rods with round, square and flat cross-section the effective and efficient method of production of ultrafine crystalline structures is based on application of repeated bending and straightening. The effectiveness of this method of microstructure comminution in strips of various copper alloys was many times tested in laboratory conditions [1, 8 - 9]. It depends on the total deformation, while the deformation in a one cycle depends on the tool geometry and on the dimensions and strength properties of the semi-products. Optimal selection of geometric parameters of the tool and the rod together with the strength parameters presents a complex problem. Fragmentation of microstructure of metals and alloys by SPD technique depends on many factors. In the studies [10-11] a model for determination of the minimum grain size during complex severe deformations was developed. The basic assumptions of the model represent a phenomenological approach of three stages of grain fragmentation:

a) high density of dislocations in the shear bands;
b) annihilation and recombination of dislocations leading to formation of dislocation cells and subgrains (recovery);
c) transformation of subgrain boundaries into high-angle boundaries.

According to that reasoning, the minimum grain size in this process results from a balance between the dislocation structure as introduced by the intense deformation and its thermal recovery. The resulting grain size depends on the size of the applied stress, energy of material stacking fault and activation energy of recovery process.

Controlled severe plastic deformation is becoming increasingly used to reach advantageous functional properties of metal products, including copper alloy strips [12-14]. Such a solution can also be applied in the manufacture of steel products. The steel of S235JR grade is the most widely used from among constructional steels. It is the most popular, the easiest from technological point of view, and its production in Poland constitute over 80% of total steel produced. Such a situation and availability of literature reports on shaping of the functional properties of steel rods through controlled plastic deformation provide incentive for studies into utilization of the formation of adiabatic shear bands to increase the strength properties of the aforementioned steel, and implementation of the results of this research into industrial practice in Poland and worldwide [15].

The objective of this study was to increase functional properties of the rods which were subjected to controlled plastic deformation by at least two classes, i.e. by increasing properties of S235JR steel up to the S355JR grade steel, in other words to change the so called "soft" (S235JR) grade to the "hard" (S355JR) grade while maintaining the chemical composition and the carbon equivalent value (CEV) at the level of S235JR grade.

2. Methodology and material for studies

In the study S235JR grade steel rods of 12 x 12 mm square cross-section and 12 mm diameter round cross-section were tested during the rolling process. Steel billets of dimensions 120 x 120 x 11700 mm obtained in continuous casting of steel (COS) were used in production of the rods. Before rolling the billets were heated up in a pusher furnace for two variants of technology. In the first variant the final temperature to be reached in rolling was 1000°C, while in the second option it was 950°C.

The studies were conducted with application of a rolling line, consisting of 7 duo rolling stands „350” (horizontal) and 8 duo finishing stands „300” and „250”- including: 4 duo horizontal and 4 duo vertical.

When rods were leaving the last rolling stand they were cooled in the air, cut with scissors into 6000 mm long segments and cooled in a cooler with a mobile grate.

After hot-rolling and normalizing a part of rods were subjected to controlled cold working deformation in a roller straightener, as presented in Fig. 1. The straightener consisted of 8 rolls (4 at the top and 4 on the bottom). The controlled cold working deformation process was performed in the first three rolls, while settings of the remaining rolls were used for straightening of the rods.

Examinations were conducted in individual stages of the manufacturing process with application of the ThermaCam SC640 thermal imaging system. Microstructure of samples of steel rods was examined by light and electron microscopy, also mechanical properties were tested.

Fig. 1 Roller straightener with a straightened by bending rod. Above and below straightener rods conspicuous mandrels for vertical control of the rolls

3. Results and discussion

3.1. Results of thermal imaging examination

Vast majority of metal processing operations is associated with heat supply or removal (cooling). Also in this studies into rolling of S235JR grade steel rods thermal phenomena took place. The delivered steel billets of dimensions 120 x 120 x 11700 mm were heated up after their loading into the pusher furnace and before hot rolling. When the defined temperature was reached the heated billets were transported through the roller table to the rolling mill and then, after dividing them into determined length, the rods were sent to the cooling unit. The thermal imaging examinations covered billets before rolling (starting rolling temperature), temperature of the rods after 15th (last) rolling stand (final rolling temperature) and changes in temperature of individual rods placed on the cooling grate.

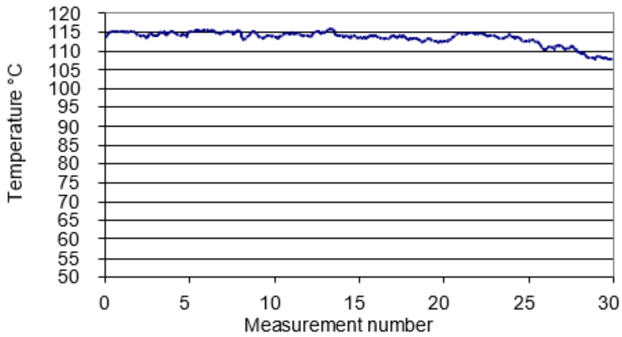

Fig. 2. Temperature distribution along the length of steel billet after leaving the furnace. The average temperature of the billet-1133°C

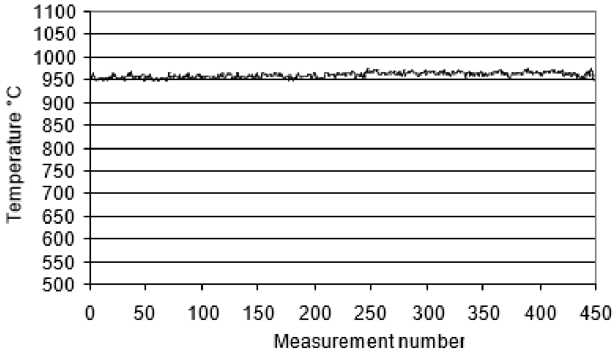

Fig. 3. Temperature distribution along the length of the rod after 15th rolling stand. Average final rolling temperature-960.50°C, duration of one passage was 120 seconds. The defined final rolling temperature 950°C

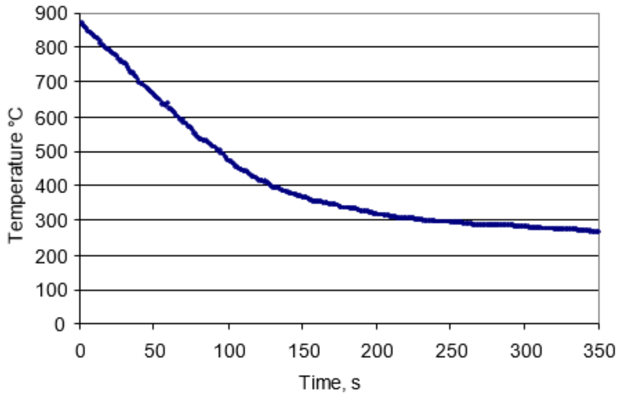

Fig. 4. Temperature distribution on individual rods during cooling from the defined final rolling temperature of 950°C

In the first place rolling of 12 mm diameter round rods was studied and then rolling of 12 x 12 mm square rods, in the two variants of final rolling temperature of 950°C and 1000°C. The temperature of billet heating in the individual zones was set in the range of 1127 - 1159°C. Figures 2-4 show sample temperature distribution along the length of the billet before rolling and during rolling and cooling of the 12 x 12 mm square rods for the final rolling temperature of 950°C.

The following average temperatures were reached with the round rods and final rolling temperature of 950°C:

- after leaving the furnace: 1130-1144°C;
- after 15th rolling stand: 983-945°C.

The following average temperatures were reached with the round rods and final rolling temperature of 1000°C:

- after leaving the furnace: 1130-1144°C;
- after 15th rolling stand: 1030-1010°C.

For the final rolling temperature of 950°C the billets which were heated up and removed from furnace before rolling had average temperature of 1142°C, and after 15th rolling stand the temperature was in the range 943-960°C.

In the rods of square cross-section and final rolling temperature of 1000°C the average temperature along the length of the rod after 15th rolling stand was in the range 1007 - 1012°C. Satisfactory temperature distributions along the length of the rolled rods were reached, considering the complex industrial conditions.

3.2. Results of microstructure examinations

Sample images of microstructure of the S235JR grade steel rods of square cross-section and dimensions 12 x 12 mm after hot rolling and cooling down in cooling unit are presented in Figures 5 - 12. Examination of microstructure was performed by light (Fig. 5-8) and scanning (Fig. 9-12) microscopy in the final rolling temperature of 950°C and 1000°C on the polished sections parallel or perpendicular to the rolling direction. It was intentionally decided to study only rods of 12 x 12 mm square cross-section, after assuming that there are no significant differences in the microstructure of rods of 12 mm diameter circular cross section. The disclosed microstructure is typical for the examined S235JR steel grade in as hot rolled condition. It consists of light areas of ferrite and dark areas of perlite (distributed along the grain boundaries) in which a lamellar structure can be observed at high magnification (Fig. 10 and 12).

Figures 5 - 6 present images of the same microstructure in the same rods, but observed (at the same magnification) on transverse and longitudinal polished sections. The band structure, mainly of perlite, is clearly visible (dark regions), which certainly diversifies properties of the tested rods in the direction parallel and perpendicular to the direction of rolling. Analogous examination of microstructure of the 12 x 12 mm S235JR steel rods was performed with the final rolling temperature of 1000°C (Figures 7 - 8). The results are identical as in the temperature of 950°C and the only difference is that the qualitative observations show slightly larger grain size of the former austenite which becomes ferrite and perlite after transformation.

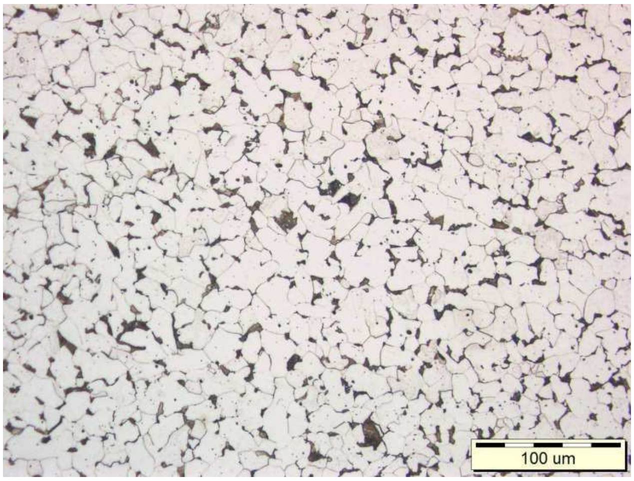

Fig. 5. Rod microstructure, polished sections perpendicular to the rolling direction, final rolling temperature of 950°C

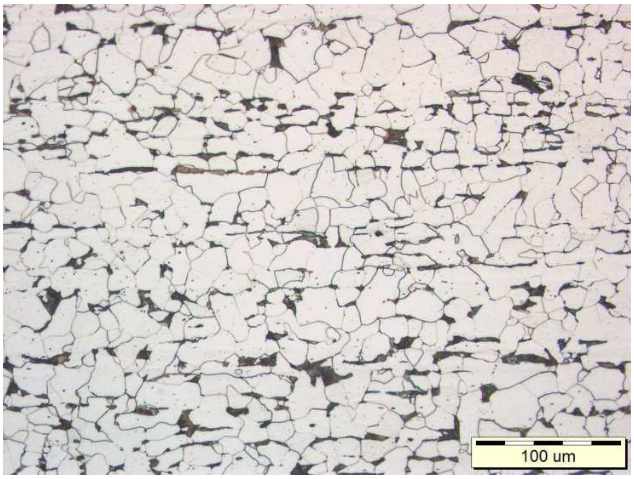

Fig. 6. Rod microstructure, polished sections parallel to the rolling direction, final rolling temperature of 950°C

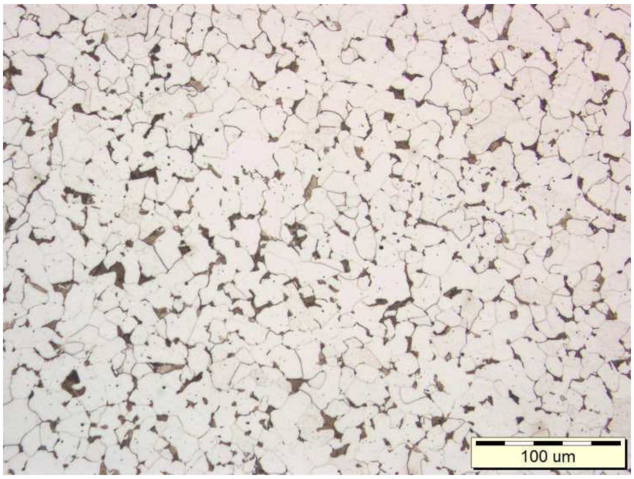

Fig. 7. Rod microstructure, polished sections perpendicular to the rolling direction, final rolling temperature of 1000°C

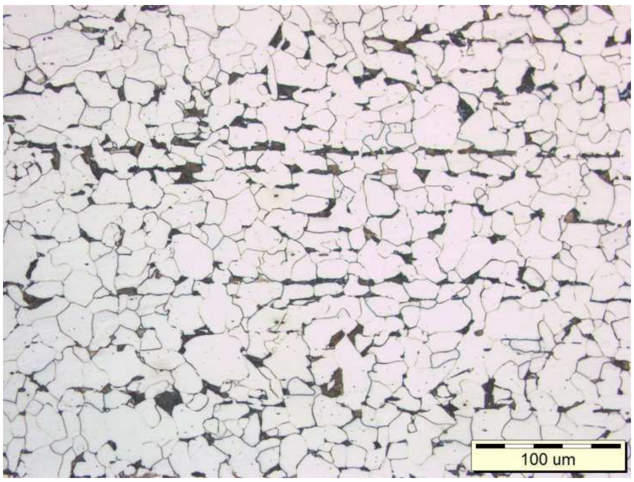

Fig. 8. Rod microstructure, polished sections parallel to the rolling direction, final rolling temperature of 1000°C

The studies into microstructure of 12 x 12 mm rods made of S235JR steel conducted on polished sections with application of a scanning electron microscope (SEM) at magnifications 1000 - 40000x resulted in observation of further details. First of all, at lower magnifications (1000x - 3000x) it was possible to observe differences in crystallographic orientation of ferrite grains which influenced intensity of the reflected electron beam. That is why some ferrite grains are lighter and other are darker. Diversified crystallographic orientation of ferrite matrix favors isotropic properties of the steel matrix, while the band distribution of perlite brings opposite effect.

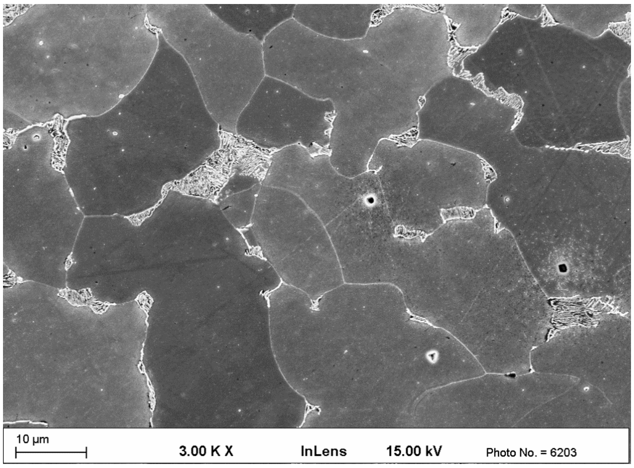

Fig. 9. Rod microstructure, polished sections perpendicular to the rolling direction, final rolling temperature of 950°C

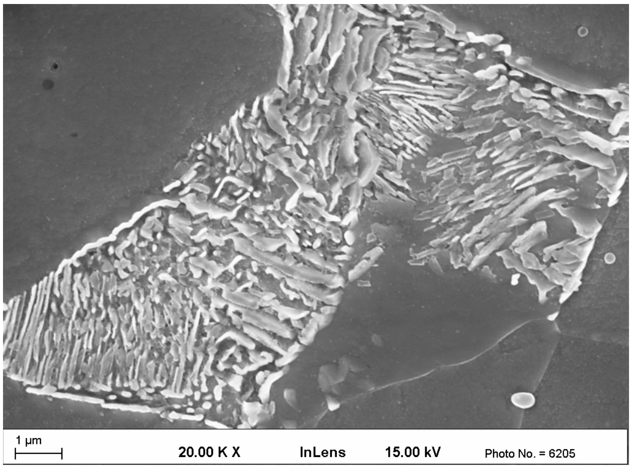

Fig. 10. Rod microstructure, polished section perpendicular to the rolling direction, final rolling temperature of 950°C

High magnification (up to 20000x) revealed details of the lamellar structure of perlite while comparison of the images of the border and central parts of the rod showed a slightly larger grain of former austenite in the middle of the rod (but in the range of ASTM grain size number of 10) as well as distribution of perlite close to the state after normalizing annealing, confirming slower cooling of the zones which are closer the rod centre.

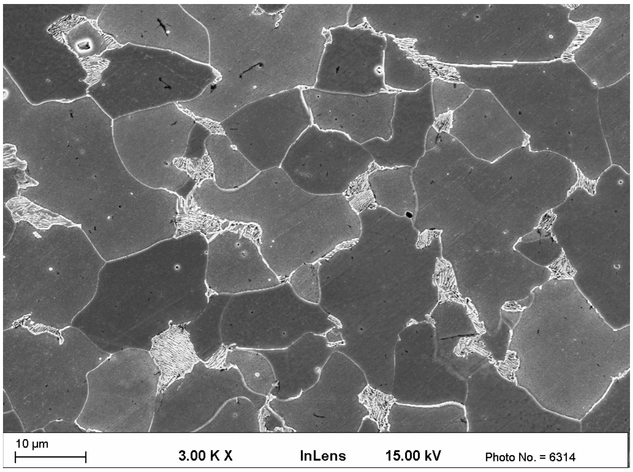

Fig. 11. Rod microstructure, polished sections perpendicular to the rolling direction, final rolling temperature of 1000°C

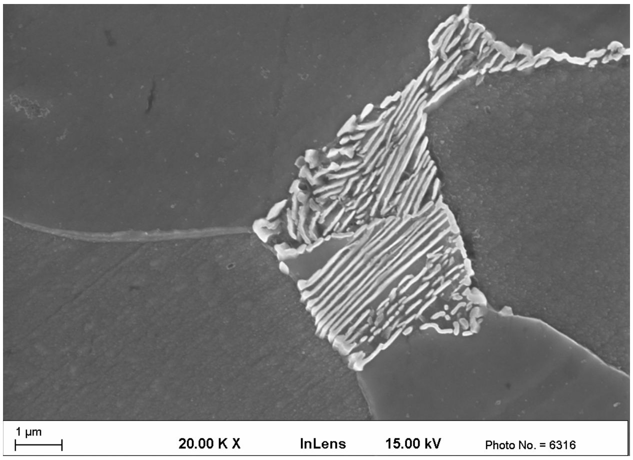

Fig. 12. Rod microstructure, polished sections perpendicular to the rolling direction, final rolling temperature of 1000°C

Similar observations can be made when analysing the registered SEM images of microstructure on longitudinal polished sections of the rods with T_{kw} = 950°C, which means that anisotropy of mechanical properties results from perlite mostly and the average grain chord in the middle of the rod is minimally larger. Additionally, the observation arises that perlite lamellae grow mainly in the direction perpendicular to the rod axis, i.e. in the direction of the highest rate of heat removal.

3.3. Examination of rods after bending

Tests of repeated bending of hot rolled rods of S235JR steel of circular-12 mm diameter, and square-12x12mm cross-section were conducted with application of universal roller straightener in dynamic and static perspective. In the studies steel rods after hot rolling, cooling down and normalizing annealing were used (Fig. 13). In the dynamic tests the rods were passed through appropriately set rolls of the straightener.

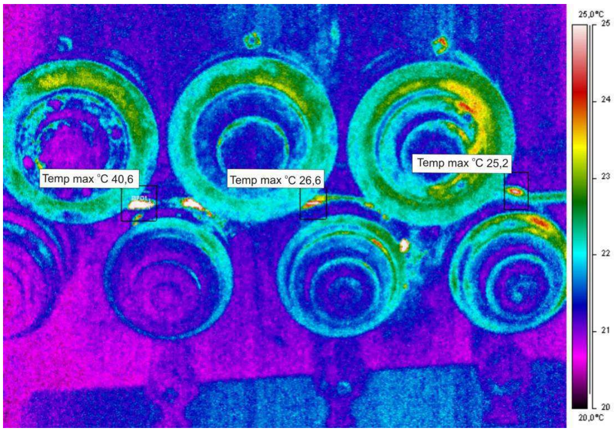

Fig. 13. Dynamic bending of hot-rolled and cooled down rod

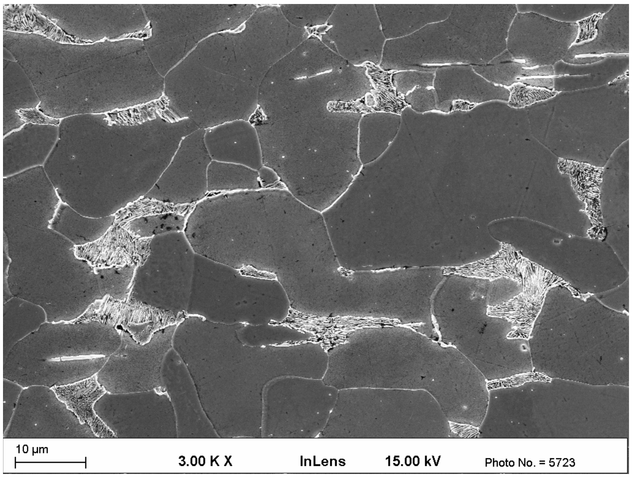

Fig. 14. Microstructure of repeatedly diagonally bent rod, polished section parallel to the rolling direction, final rolling temperature 950°C

Figure 13 shows a thermal image and locations of temperature measurement during bending of a subsequent rod. The temperature of the initial fragment of the rod increased gradually in the individual pairs of straightening rolls to reach 40.60°C in the third pair. From thus deformed rods appropriate number of samples was taken for microstructure examination. Because of wide range of the examination the paper presents examples of characteristic images of the microstructure for the applied different variants of strains and carefully selected examination methods (Fig. 14 -1 7). Microstructure of the rods was similar to the microstructure before deformation. The arrangement of perlite lamellae as observed in the rods after bending was more random, and some of them were crushed, therefore the process of bending should positively influence (decrease) anisotropy of mechanical (plastic) properties.

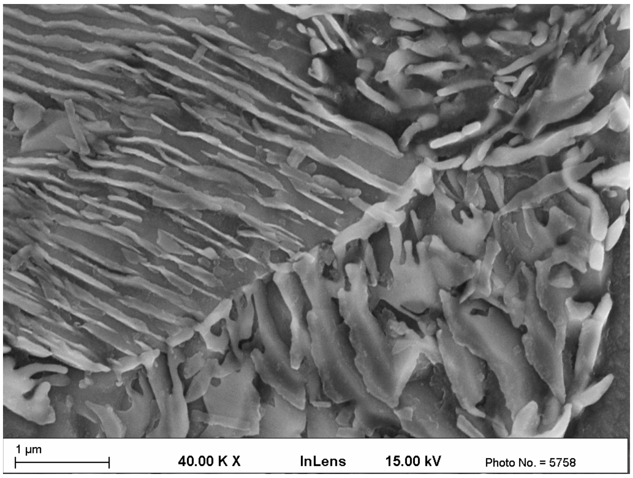

Fig. 15 Microstructure of repeatedly diagonally bent rod, polished section parallel to the rolling direction, final rolling temperature 950°C

The analysis of hardness measurements as shown in Table 1 indicates that application of the cold working deformation after hot-rolling of rods leads to increasing strength indicators at insignificantly decreasing indicators of plasticity (elongation and reduction of area) and fracture toughness (impact strength). The ultimate tensile strength increased by about 5%, while the upper yield stress and hardness by about. 10%. The obtained tensile strength values are within the range 360 - 510 MPa as required by PN-EN 10025-2:2004 standard for rods made of S235JR steel.

The high yield stress value after rolling of rods, reaching even 360 MPa-(at the required 235 MPa- according to the given above standard) deserves some attention. Application of cold working deformation, however, caused increased strength indicators of rods at insignificantly decreased plasticity indicators (elongation and reduction of area) and fracture toughness (impact strength).

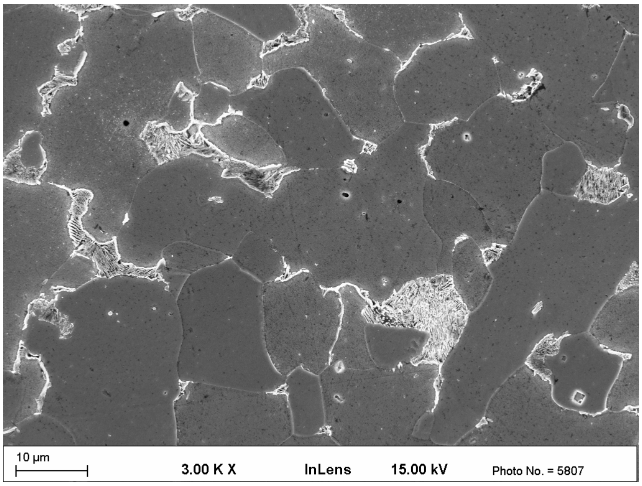

Fig. 16. Microstructure of repeatedly diagonally bent rod, polished section parallel to the rolling direction, final rolling temperature 1000°C

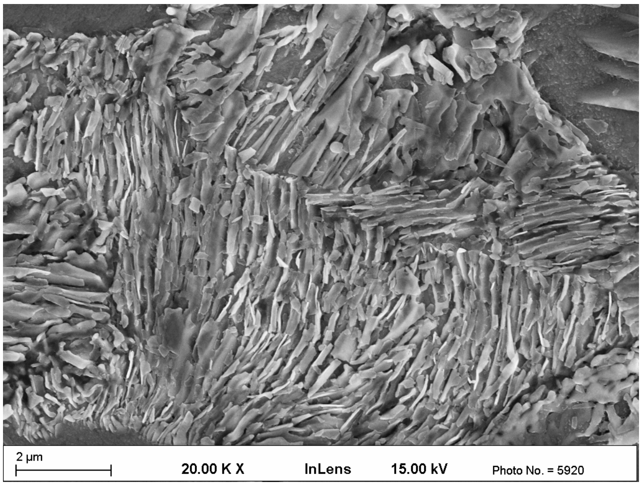

Fig. 17. Microstructure of repeatedly diagonally bent rod, polished section parallel to the rolling direction, final rolling temperature 1000°C

Based on the results of the performed tests simulation studies of bending process by finite element method were conducted. Firstly input data were developed to perform simulation studies into the process of controlled cold deformation of S235JR steel. In the theoretical analysis of steel rod bending processes a Forge2011® computer program was used. For application of the computer program and its thermo-mechanical models it was necessary to define the boundary conditions which determine accuracy of numerical calculations. The results of calculations are specifically influenced by: properties of the tested materials, conditions of friction as well as kinetic and thermal parameters describing the bending process.

Table 1.
The results of tensile test, impact test and hardness measurements of S235JR steel samples

Variant	UTS, MPa	YS, MPa	EL, %	HV30
950	479	360	35	134
950+RCS	505	401	31	152
1000	471	356	34	137
1000+RCS	499	392	32	150

Variants:
950 – final rolling temperature 950°C,
950+RCS final rolling temperature 950°C and bending,
1000 – final rolling temperature 1000°C,
1000+RCS final rolling temperature 1000°C and bending.

In development of flow stress function, the following form of Hensel-Spittl equation was selected:

$$\sigma_p = A\exp(m_1 T)\varepsilon^{m_2}\dot{\varepsilon}^{m_3}\exp(\frac{m_4}{\varepsilon}) \qquad (1)$$

where:
ε – substitute strain,
$\dot{\varepsilon}$ – strain rate, s^{-1},
T – temperature, °C,
A, m_1, m_2, m_3, m_4 – coefficients determined in plasticity studies

The determined functions of flow stress of examined materials were implemented in the Forge2011® software. The following border conditions were accepted for the simulations:

- temperature of tools and ambient temperature – 20°C,
- initial temperature of deformed rod – 20°C,
- coefficient of heat exchange between the deformed material and tool - adiabatic,
- friction coefficient – 0.05
- rotational speed of rolls v = 36 rev/min.

Three-dimensional models produced in CAD type software were used in the studies into controlled process of cold deformation of S235JR steel (Fig. 18).

The "MES" can be used to trace changes in temperature, state of strain and stresses generated during plastic working processes. In order to describe the temperature distribution in the 12 x 12 mm square rod during its plastic deformation the temperature on the surface and in the cross-section of the rod at each stage to its bending was measured. The rod temperature increased at the contact point of the rod and the rolls of the straightener to about 55°C, which resulted from the release of heat of plastic deformation and friction. The temperature in the axis of the rod during bending was at the level of 35°C.

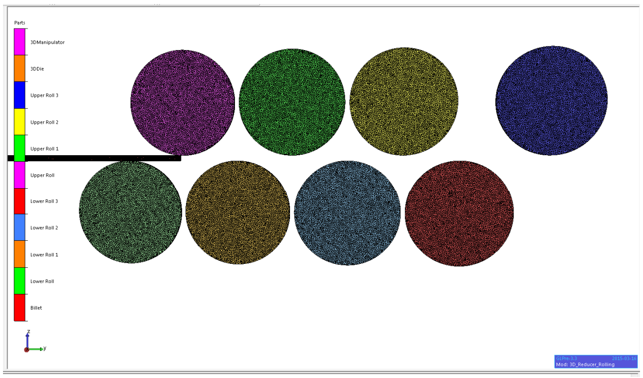

Fig. 18. Finite element mesh of the geometrical model of process of steel rods bending prepared in FORGE2011 software

The strain in the analyzed rod was distributed in a form of layers, and the highest values were recorded in the surface layers close to the contact zone with the tool, while the lowest in the axis of the rod. The substitute strain on rod surface was at the level of 0.11.

According to the Huber-Mises hypothesis the values of strains generated in the rods (so called substitute-equivalent strains) in the analyzed examples increased in the contact area between the rod and a straightener roll, never exceeding the value of 800 MPa.

4. Conclusions

The microstructure of the examined S235JR steel is a typical one for the as hot rolled state. It consists of light areas of ferrite and dark areas of perlite (arranged in the area of grain boundaries), in which at high magnification of transmission electron microscopy lamellar structure can be observed.

The band arrangement of perlite differentiates properties of tested rods in the longitudinal direction (KW) and in the transverse direction (KP) to the direction of rolling.

Both in the initial stage and after different bending variants no significant differences in the size of ferrite as well as perlite grains in the studied samples were observed.

The perlite lamellae in the initial material grew mainly in the direction perpendicular to the axis of the rod, i.e. in the direction of the highest rate of heat dissipation.

Arrangement of the perlite lamellae as observed in the bent rods was more random, and some of them were crushed. The process of bending should therefore positively influence (decrease) anisotropy of mechanical (plastic) properties.

The conducted studies of rod bending simulation which included examination of temperature distribution are consistent with experimental thermal imagining studies. The value of the substitute strain on the rod surface was about 0.11, while the stress in the contact area between the rod and a straightening roll never exceeded 800 MPa.

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Additional information

Selected issues related to this paper are planned to be presented at the 22nd Winter International Scientific Conference on Achievements in Mechanical and Materials Engineering Winter-AMME’2015 in the framework of the Bidisciplinary Occasional Scientific Session BOSS'2015 celebrating the 10th anniversary of the foundation of the Association of Computational Materials Science and Surface Engineering and the World Academy of Materials and Manufacturing Engineering and of the foundation of the Worldwide Journal of Achievements in Materials and Manufacturing Engineering.

References

[1] J. Stobrawa, Z. Rdzawski, W. Głuchowski, W. Malec, Ultra fine grained strip of precipitation hardened copper alloys, Archives of Metallurgy and Material, 56/1 (2011) 171-179.

[2] A. Mishra, B. K. Kad, F. Gregori, M.A. Meyers, Microstructural evolution in copper subjected to severe plastic deformation: Experiments and analysis, Acta Materialia 55 (2007) 13-28.

[3] J. Gubicza, N.Q. Chinh, T. Csanadi, T.G. Langdon, T. Ungar, Microstructure and strength of severely deformed fcc metals, Materials Science and Engineering A 462 (2007) 86-90.

[4] M. Greger, R. Kocich, L. Cizek, L.A. Dobrzański, M. Widomska, B. Kuretova, A. Silbernagel, The structure and properties of choosen metals after ECAP, Journal of Achievements in Materials and Manufacturing Engineering 18/1-2 (2006) 103-106.

[5] X-W Li, Q-W Jiang, Y. Wu, Y. Wang, Y. Umakoshi, Stress-amplitude-dependent deformation characteristics and microstructures of cyclically stressed ultrafine-grained copper, Advanced Engineering Materials 10/8 (2008) 720-726.

[6] I.H. Son, Y.G. Jin, J.H. Lee, Young-TaekIm, Load predictions for non-isothermal ECAE by finite element analyses, International Journal of Computational Materials Science and Surface Engineering 1/2 (2007) 242-258.

[7] M. Kulczyk, W. Pachla, A. Mazur, M. Suś-Ryszkowska, N. Krasilnikov, K.J. Kurzydłowski, Producing bulk nanocrystalline materials by combined hydrostatic extrusion and equal-channel angular pressing, Materials Science 25/4 (2007) 991-999.

[8] J. Stobrawa, Z. Rdzawski, W. Głuchowski, W. Malec, Microstructure evolution in CRCS processed strip of CuCr0,6 alloy, Journal of Achievements in Materials and Manufacturing Engineering 38/2 (2010) 195-202.

[9] J. Stobrawa, Z. Rdzawski, W. Głuchowski, W. Malec, Microstructure and properties of CuNi2Si1 alloy processed by continuous RCS method, Journal of Achievements in Materials and Manufacturing Engineering 37/2 (2009) 466-479.

[10] F.A. Mohamed, A dislocation model for the minimum grain size obtainable by milling, Acta Materialia 51 (2003) 4107-4119.

[11] H.J. Fecht, Nanostructure formation by mechanical attrition, Nanostructured Materials 6 (1995) 33-42.

[12] W.J. Głuchowski, J. Domagała-Dubiel, J. Sobota, J.P. Stobrawa Z.M. Rdzawski, Copper, brass and bronze strips with controlled properties by RCS method, Archives of Materials Science Engineering 60/2 (2013) 53-63.

[13] W. Kwaśny, P. Nuckowski, Z. Rdzawski, W. Głuchowski, Influence of RCS process on the structure and mechanical properties of CuSn6 alloy Archives of Materials Science Engineering 62/2 (2013) 60-66.

[14] W. Głuchowski, J. Domagała-Dubiel, J. Stobrawa, Z. Rdzawski, J. Sobota, Effect of continuous RCS deformation on microstructure and properties of copper and copper alloys strips Key Engineering Materials 641 (2015) 294-303.

[15] J. Pacyna, R. Dąbrowski, E. Rożniata, A. Kokosza, R. Dziurka, Microstructure and mechanical properties of structural steel after dynamic cold working deformation, Archives of Metallurgy and Materials 59/4 (2014) 125-131.