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MICROSTRUCTURE AND MECHANICAL PROPERTIES OF STRUCTURAL STEEL AFTER DYNAMIC COLD WORKING DEFORMATION

WPŁYW DYNAMICZNEGO ODKSZTAŁCENIA PLASTYCZNEGO NA ZIMNO NA MIKROSTRUKTURĘ I WŁASNOŚCI STALI KONSTRUKCYJNEJ

The results of the selected mechanical properties i.e. ultimate tensile strength (UTS), yield stress (YS), elongation (EL), reduction of area (RA), hardness (HV) and impact strength (KCV) of the common, S235JR grade steel, are presented in the paper. A strong relationship between the above mentioned properties and cooling rates after hot rolling of rods, made of this steel, was found.

Additionally, the possibility of further enhancing of mechanical properties (UTS and YS) by the controlled, dynamic cold working, was shown. The use of such deformation, through changes in the microstructure allows for the upper yield stress (YS) increase – app. 10% and ultimate tensile strength UTS – app. 5%.

Simultaneously, very high indicators of plasticity (EL, RA) and impact strength (KCV) are retained, as they were immediately after the rolling. The possibility of improving the mechanical properties of rods made of this steel grade has a great technological and commercial importance for its manufacturers, as well as for their final users.

Keywords: structural steel, microstructure, cold working, mechanical properties

W pracy zamieszczono wyniki badań wybranych własności mechanicznych (R_m, R_{eH}, A, Z, HV, KV) popularnej stali niestopowej w gatunku S235JR, wskazując na silny wpływ szybkości chłodzenia prętów z tej stali po walcowaniu na gorąco. Dodatkowo, pokazano możliwość dalszego zwiększenia własności wytrzymałościowych (R_m, R_{eH}) przez zastosowanie kontrolowanego, dynamicznego odkształcenia plastycznego na zimno. Zastosowanie takiego odkształcenia, poprzez zmiany w mikrostrukturze, umożliwia uzyskanie wzrostu górnej granicy plastyczności R_{eH} o ok. 10%, wytrzymałości na rozciąganie R_m o ok. 5% przy zachowanych, tak jak w stanie bezpośrednio po walcowaniu, bardzo wysokich wskaźnikach plastyczności (A, Z) i odporności na pękanie (KV). Możliwość poprawy własności mechanicznych prętów wytwarzanych z tej popularnej stali ma duże znaczenie technologiczne i handlowe dla jej wytwórców, jak również duże znaczenie dla ich końcowych użytkowników.

1. Introduction

Unalloyed steels constitute the group of steels widely used in civil and industrial building. Elements made of these steels are joined by welding, riveting or screw joints. These steels are supplied in hot-rolled state as products both flat and long, it means in forms of sheets, tapes, shaped elements and rods [1]. The widest application among structural steel has the S235JR grade, the most popular, and the easiest technologically, which production in Poland constitutes over 80% of the produced steel. Universality of this steel occurrence and relatively easy its production technology encourages attempts of looking for improvements of its mechanical properties. The microstructure and properties of metallic materials can be formed by means of plastic working. The deformation process occurs in a different way in case of materials of fcc [2÷6] or bcc [7÷9] structure. In the investigated case the S235JR steel was hot-rolled, that is there was a plastic deformation in the fcc structure range combined with a dynamic recrystallisation [3, 5]. Nevertheless the final ferritic-pearlitic microstructure, formed as a result of a diffusive transformation, was the initial microstructure for the strain hardening due to the cold working deformation. In this case, these transformations are related to the strain hardening in the bcc state [7, 8]. Several techniques of large intensive plastic deformations, leading to obtaining the controlled microstructure, are known in the world [10]. In case of steel rods of round and square cross-sections the method of cyclic bending and straightening seems to be the efficient and effective way to obtain the needed microstructure. The application of this method in case of steel rods should lead to increasing the ultimate tensile strength being the result of the microstructure refinement causes by the dynamic cold working deformation at slightly decreasing plasticity indices (elongation, reduction of area) and fracture toughness (impact strength). Several factors influence the final mechanical properties of steel, after the controlled cold working deformation: temperature of the rolling end (grain size of a prior austenite in crude rods), cooling rate of rods after the last rolling stand and carbon and

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TABLE 1
Chemical composition of the S235JR steel acc. to standard PN-EN 10025-2:2005 and the chemical composition of steel billets intended for hot-rolling

Chemical composition, wt.%	C	Mn	Si	P	S	Cr	Ni	Cu	Mo	V
PN-EN 10025-2:2005 specification	max 0.17	max 1.40	–	max 0.035	max 0.035	–	–	0.55	–	–
Analysis	0.15	0.61	0.22	0.023	0.022	0.06	0.08	0.24	0.02	0.003

other alloying elements content in the chemical composition of steel determined in standard: PN-EN 10025-2:2005.

Endeavours to assess the influence of the dynamic cold working deformation – caused by cyclic bending – on the microstructure and mechanical properties of rods (of square cross-section) made of the S235JR steel, previously hot-rolled at two different temperatures of the process end were undertaken. The obtained results are of a scientific and cognitive character, while the possibility of the improvement of mechanical properties of rods of this steel is of a high technological and market importance for its producers and users.

2. Research material

Steel billets of the S235JR grade of dimensions 120×120×11700 mm obtained in the Continuous Casting of Steel process in Ferrostal Łabędy, were charge materials for the rods production.

The chemical composition of the S235JR steel, acc. to standard PN-EN 10025-2:2005, and the chemical composition of steel billets intended for hot-rolling are given in Table 1.

3. Experimental procedure

Rolling of billets of the given above dimensions to reduce their cross-section to the final value 12×12 mm was performed in the technological line of the Ernst Thalmann Company, consisting of 7 break-down stands and 8 finishing stands, in the Profil S.A. Rolling Mill in Krakow. Two temperatures of the rolling end were applied: 950 and 1000°C.

When rods were leaving the last rolling stand they were cooled in the air, cut on scissors into segments 6000 mm long and cooled in the cooler with a mobile grate. Then, after cooling, rods were cut by scissors for the needed length and from them samples for laboratory tests being carried out in the AGH University of Science and Technology, were cut out.

After hot-rolling a part of rods were subjected to the controlled cold working deformation in the roller straightener, which is shown in Fig. 1.

The straightener consists of 8 rolls (4 at the top and 4 on the bottom). The controlled cold working deformation process was realised in the first three rolls, while settings of the remaining rolls were used for straightening of rods. The plastic deformation of rods was done by double-sided flat bending.

Ac_3 temperature occurring during heating of the S235JR steel were measured by the dilatometric method using an L78 R.I.T.A dilatometer of the German Linseis Company. Sample elongations resulting from the temperature changes were recorded digitally. Samples with dimensions of Ø3×10 mm were heated from room temperature to 1100°C at the rate 180°C/hour. The heating curve was differentiated $\Delta(\Delta L/\Delta T)=f(T)$, (where: ΔL – is a length change of the sample, ΔT – is a temperature change of the sample, T – temperature).

Fig. 1. Photograph of the roller straightener used for the controlled cold working deformation of rods of the S235JR steel

Microscopic examinations were performed on the light microscope Axiovert 200 MAT of the Zeiss Company.

Mechanical tests of the S235JR steel comprised tensile test, impact test and hardness measurements. Static tensile test has been performed using a computer controlled MTS-810 testing machine acc. to PN-EN 10002-1/2005. Proportional test pieces have been used with initial diameter of 8 mm. During this test the following data have been determined: UTS, YS, EL, RA.

The impact test were performed acc. to PN-EN 10045-1/1994, using the 300 J Charpy tester.

Fracture surfaces of impact test specimens were also observed.

Hardness has been measured using Vickers apparatus with 294 N indender load.

4. Results and discussion

The example of the dilatometric curve of heating the S235JR steel sample taken from the rod after rolling, together with the corresponding differential curve is presented in Fig. 2.

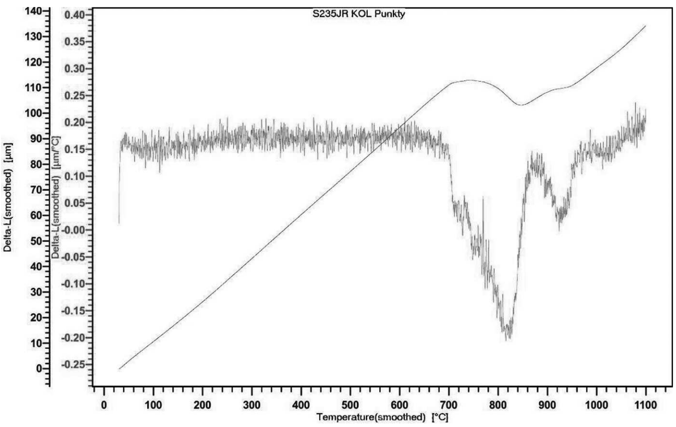

Fig. 2. The dilatometric curve ΔL=f(T) of heating the S235JR steel to 1100°C at the rate of 3°C/min after hot rolling

On the basis of the dilatometric curve of heating the S235JR steel sample the end temperature of the ferrite transition into austenite was estimated as being 950°C.

It should be mentioned that the temperature of 950°C is the temperature of the end of rolling applied under technical conditions in the Profil S.A. Rolling Mill the application of this temperature as well as the proper cooling rate behind the last rolling stand should assure obtaining the required, by PN-EN 10025-2:2004, mechanical properties of the S235JR steel, i.e. YS = 235 MPa, UTS = 360÷510 MPa and $KV_{+20°C}$ = 27 J.

TABLE 2

Detailed description of rods of the S235JR steel hot-rolled and cold deformed

Variant	Variant description
I	Rods of a cross-section 12x12 mm after rolling, **T_{ER} = 950°C**
IA	Rods after rolling, (as I) subjected to the controlled cold working deformation (double-sided flat bending)
II	Rods of a cross-section 12x12 mm after rolling, **T_{ER} = 1000°C**
IIA	Rods after rolling, (as II) subjected to the controlled cold working deformation (double-sided flat bending)

Microstructures of the S235JR steel samples in the cross-section of rods according to variants given in Table 2.

As can be seen (Fig. 3) the microstructure of square bars after rolling as well as after cold working deformation is very similar and consists of bright ferrite zones and dark zones of fine pearlite, arranged along ferrite grain boundaries. On the bases of a qualitative observations it is possible to notice clearly larger grains of prior austenite, when T_{ER} = 1000°C (Fig. 3c, d). However, measurements performed according to ASTM recommendations indicate that the grain-size number should be equal 10 both for T_{ER} = 950°C and T_{ER} = 1000°C. The comparison of microstructures of steel samples after rolling and after cold working deformation for T_{ER} = 950°C (see Fig. 3a and b) and for T_{ER} = 1000°C (see Fig. 3c and d) carried out by the light microscope, does not indicate finer ferrite grains in rods after their cold working deformation. Acc. to Ref. [9] the application of intensive, controlled cold working deformation should cause the local formation of the so-called adiabatic shearing bands. In places of their formation the temperature should significantly increase causing local, dynamic recrystallisation leading to refinement of grains existing directly after rolling. This refinement of grains should cause a yield strength and ultimate tensile strength of rods. The fact that during microscopic observations the refinement of ferrite grains was not seen requires further investigations with the application of the transmission electron microscopy and detailed thermovision tests during the static deformation of rods – to determine the local temperature increase value (during this deformation) and thus to confirm the grains refinement caused by adiabatic shearing bands (mentioned above).

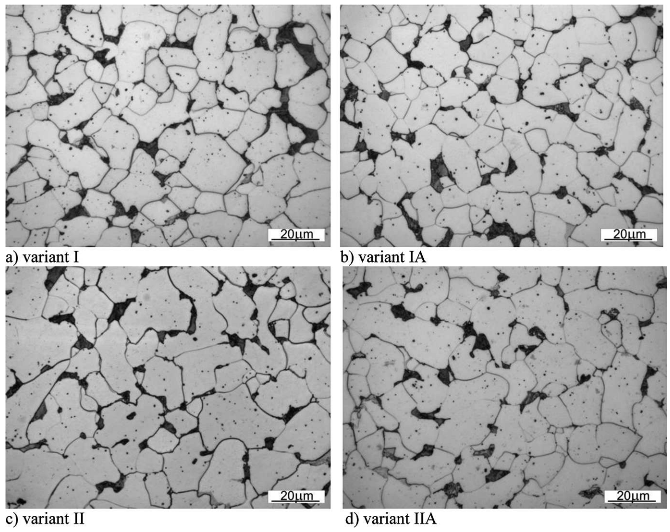

Fig. 3. Microstructures of the S235JR steel samples in the cross-section of rods, according to variants given in Table 2

Results of metallographic tests of structural components of samples obtained from rods of the S235JR steel, according to variants given in Table 2.

TABLE 3

Results of metallographic tests of structural components of samples obtained from rods of the S235JR steel are presented in Table 3, acc. to variants given in Table 2

Variant	Volume fraction of pearlite, %	Volume fraction of ferrite, %	Average cross-sectional area of ferrite and pearlite grains, μm^2	Grain-size number acc. to ASTM
I	15±2	85	140±12	10
IA	13±4	87	158±16	10
II	18±3	82	176±22	10
IIA	14±3	86	198±10	10

Small differences in cooling rates in the range 800÷500°C being 3.9°C/s for T_{ER} = 950°C and 4.1°C/s for T_{ER} = 1000°C, as well as applying of the further controlled cold working deformation did not cause essential changes in volume fractions of ferrite and pearlite.

The detailed results of mechanical properties of the S235JR steel samples after rolling and cold working deformation are shown in Table 4.

TABLE 4
The results of tensile test, impact test and hardness measurements of the S235JR steel samples, acc. to variants given in Table 2

Variant	YS (MPa)	UTS (MPa)	EL (%)	RA (%)	HV 30	KV (J)
I	360±5	479±1	34.6±1.2	70.9±0.5	134±1	154±4
IA	401±5	505±1	30.9±0.7	68.7±0.4	152±2	151±3
II	356±5	471±1	33.7±1.7	68.0±3.7	137±1	153±5
IIA	392±9	499±1	31.6±1.6	66.2±1.1	150±2	152±2

The analysis of data shown in Table 4 indicates that the 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 app. 5%, while the upper yield stress and hardness by app. 10%. The obtained tensile strength values are within the range 360÷510 MPa required by PN-EN 10025-2:2004 for rods made of the S235JR steel. The high yield stress value obtained after rolling of rods, being even 360 MPa – (at the required 235 MPa – acc. to the given above standard) deserves attention. These high yield stress values can be the result of the accelerated cooling, when rods are leaving the last rolling stand. Rods cooled in such way, under technical conditions of the Profil S.A. Rolling Mill can contain an increased energy amount, thus causing the high yield point value. In order to achieve the thermodynamic equilibrium in the tested rods and to lower strength indicators, including the yield stress, these rods should be subjected to the normalising annealing.

The increased strength indicators of the rods, of the S235JR steel, are accompanied by a high ductility determined in the impact test. The impact energy (KV) is within the range 151÷154 J, it means is nearly 6-times higher than the required by the standard PN-EN 10025-2:2004 value of 27 J. High impact energy values were confirmed by the macroscopic observations of samples as well as by fractographic studies (Fig. 4).

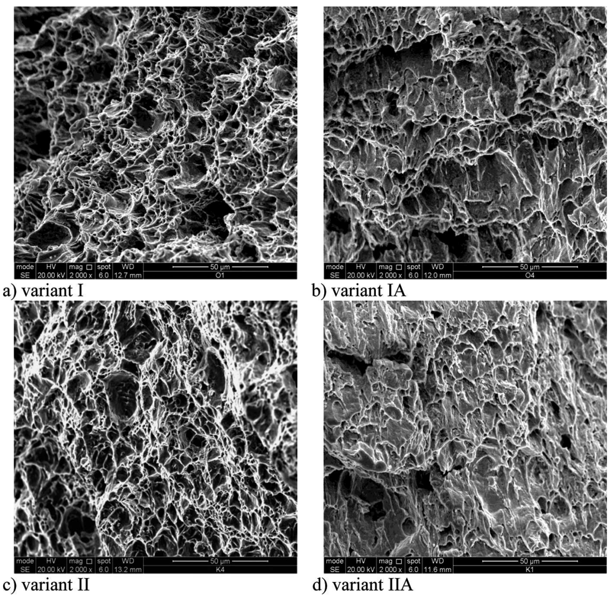

Fig. 4. Fracture surfaces of impact strength specimens (SEM)

Fractures of the S235JR steel samples taken from square rods after rolling and after cold working deformation are of a very similar character. Those are ductile pitted fractures with a large number of characteristic 'voids'. In case of the sample subjected to the cold working deformation, after rolling from T_{ER} = 1000°C (Fig. 4b), flat spaces indicating quasi-brittle fractures are seen locally. The most ductile fracture was observed in the sample subjected to a plastic deformation, according to No. II variant (Fig. 4c).

5. Summary

The assessment of microstructures and mechanical properties of square rods of the S235JR steel, after hot-rolling as well as changes of these values after the controlled cold working deformation, was performed in the hereby paper. The aim of this deformation was the introduction of essential changes in the microstructure obtained after hot-rolling of rods. The microstructure analysis as well as the metallographic investigations with using the light microscopy did not reveal essential differences between these states. However, the application of this cold working deformation caused increased strength indicators of rods at insignificantly decreased plasticity indicators (elongation and reduction of area) and fracture toughness (impact strength). An increase of the ultimate tensile strength by app. 5% was noticed, why the yield stress and hardness increased by app. 10%.

The obtained results will allow to explain effects causing the increase of the functional properties of steel rods, after the controlled cold working deformation process. However, regardless of the reasons of its occurrence, the effect of increasing the functional properties of rods is technologically and commercially important both for the manufactures and final users of rods. It can be utilised in production processes of other steel grades as well as round rods, e.g. of non-ferrous metals alloys in small and middle size enterprises having at their disposal the rod straightener to straighten rods before sending them to clients.

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