UDK 669.018.254
Professional article/Strokovni članek

ISSN 1580-2949
MTAEC9, 47(5)665(2013)

INFLUENCE OF THERMOMECHANICAL PROCESSING ON THE COLD DEFORMABILITY OF LOW-CARBON STEEL

VPLIV TERMOMEHANSKE PREDELAVE NA HLADNO PREOBLIKOVALNOST MALOOGLJIČNEGA JEKLA

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Prejem rokopisa – received: 2012-08-31; sprejem za objavo – accepted for publication: 2013-01-29

The group of steels intended for the production of bolts and nuts from the production programme of the Zenica Steel Plant, Zenica, nowadays called Arcelor Mittal Zenica, includes, among others, the steel C8C according to EN 10263-2. In this paper, the results of testing the above-mentioned steel, with the nitrogen content of more than 0.007 %, manufactured within a specifically defined technological programme, are presented. The testing of the rolled bars with a diameter of 12 mm is focused, among the mechanical and metallographic tests, especially on the technological compression test in the cold state that is normally performed as an additional control test in the production. The cold compression of the test samples has been performed in four degrees of deformation and at two different speeds of compressing tools. We determined the dependence of the resistance to deformation of the material on the degree and speed of deformation. The surface inspection of the tested samples was performed with visual control with the aim to determine deformability of the bars produced in this way.

Keywords: low-carbon steel, deformation testing, compression, visual control

Skupina jekel, namenjena za izdelavo vijakov in matic iz proizvodnega programa Železarne Zenica iz Zenice, danes Arcelor Mittal Zenica, vsebuje med drugim tudi jeklo C8C, skladno s standardom EN 10263-2. V članku so predstavljeni rezultati preizkušanja omenjenega jekla z vsebnostjo dušika več kot 0,007 %, izdelanega po posebni tehnologiji. Preizkušanje valjanih palic premera 12 mm je poleg metalografskih in mehanskih preizkusov usmerjeno predvsem na tehnološki tlačni preizkus v hladnem, kar se navadno izvaja kot dodatni kontrolni preizkus v proizvodnji. Preizkus hladnega stiskanja vzorcev je bil izvršen s štirimi stopnjami deformacije in pri dveh hitrostih stiskanja. Določena je bila odvisnost med odpornostjo proti deformaciji materiala, stopnji deformacije in hitrosti deformacije. Ocena površine preizkušancev je bila izvršena z vizualnim nadzorom z namenom, da se ugotovi deformabilnost palic.

Ključne besede: maloogljično jeklo, preizkus deformacije, stiskanje, vizualni nadzor

1 INTRODUCTION

Aluminum is used as a deoxidizing agent during the production of low-carbon steels included in the standard EN 10263-2. This type of deoxidation creates favorable conditions for obtaining the steels with a high capability of being shaped in the cold state. Parallel to the process of binding oxygen to aluminum, aluminum also binds nitrogen in aluminum nitride (AlN) precipitates that, according to the known Zener mechanism of the grain boundary pinning,[1] block the growth of the austenite grains in the process of static and dynamic recrystallization and during the thermomechanical rolling process. In the usual process of thermomechanical rolling, according to the original MORGAN technology for the wire rolling mill, we obtain the steel with a fine-grained microstructure (ASTM8–ASTM10). The microstructure of this type of steel is characterized with the increased values of the yield strength and with a high resistance to plastic deformation and decreased plasticity.[2] Insufficient plasticity of this steel type is the result of strengthening through a reduction of the ferrite-grain size, the presence of aluminum in the crystal lattice and the presence of aluminum nitride precipitates.

Sensitivity of this steel to cold deformation depends on the manner of nitrogen binding in the steel. Namely, if nitrogen is interstitially dissolved in the α-Fe crystal lattice during the process of natural aging, it will bind to iron in Fe_4N. This is directly connected to an increased sensitivity of the steel to cold deformation. This sensitivity increases with an increase in the nitrogen content in the steel. But, if nitrogen is in the form of aluminium nitride then the sensitivity of the steel to cold deformation decreases.

Particle precipitates and grain boundaries are obstacles for dislocation motion. With an increased number of these obstacles, the resistance of the steel to deformation increases and the plasticity of the steel decreases. Non-coherent precipitates are weaker obstacles for dislocation motion than coherent precipitates because dislocations, during their motion round the non-coherent precipitates, form Orowan loops around such precipitates.[3] The formation of Orowan loops represents the initial reaction of the dislocation with the precipitates and a continuation of the plastic deformation, which is accompanied by a deformation strengthening, a further reaction. The external load to be applied to cause the initial reaction and to reach the yield stress represents a measure of precipitation hardening, while an additional increase in the load, allowing a continuation of the reaction represents a measure of deformation strengthening.

2 EXPERIMENTAL WORK

Sixteen experimental heats with a weight of 120 t were produced in the LD converters. The chemical compositions of all the heats are within the permissible limits for the steel C8C according to the standard EN 10263-2 (**Table 1**).

Table 1: Chemical composition according to standard EN 10263-2
Tabela 1: Kemijska sestava, skladna s standardom EN 10263-2

Steel	Content of elements in mass fractions (*w*/%)					
	C	Si_{max}	Mn	P_{max}	S_{max}	Al
C8C	0.06–0.10	0.10	0.25–0.45	0.020	0.025	0.020–0.060

All the produced heats were hot rolled into the semi-products with the dimensions of 115 mm × 115 mm × 12000 mm, and then into the wires with the diameters from 6 mm to 12 mm using a MORGAN – USA wire rolling mill. Eight heats were processed according to the original technological prescriptions defined by MORGAN and the remaining eight heats were processed according to the corrected prescriptions related to the heating of semi-products and the corrected prescription related to the thermomechanical treatment (rolling and cooling). In the phase of the semi-product heating a longer stay of a semi-product in the walking-beam furnace was provided for by increasing the rolling rhythm from 13 s to 16 s, depending on the diameter of the rolled wires. A longer stay of the semi-products in the walking-beam furnace enables the coarsening of the aluminium nitride precipitates. By reducing the semi-product temperature in the walking-beam furnace by 50 °C we reduced the possibility of a complete dissolution of the aluminium nitride precipitates in the matrix after achieving Ostwald ripening[4] at a temperature above 1150 °C. Through an equable rolling rhythm it was provided that the final rolling temperature was between 950–980 °C with the aim of creating the conditions for the static and dynamic recrystallization of the austenite so as to ensure coarse grains in the structure after the phase austenite-ferrite transformation, which is more suitable for further cold plastic deformation. The reduction of the cooling speed after the final rolling pass by stopping the forced cooling and the reduction of the speed of the STELMOR conveyor from 25 m/min to 19 m/min had similar effects. A slow cooling of the rolled wire provides better conditions for the static recrystallization and a growth of the recrystallized austenitic grains. Also, according to Beeghly,[5,6] a lower cooling rate creates favourable conditions for a precipitation of aluminium nitride particles in the temperature interval of 950–750 °C in the steel matrix. In this way we prevented dissolution of the nitrogen in the ferrite crystal lattice that is a result of the natural aging process in the steel and of the intense deformation strengthening of the steel during the cold plastic deformation.

The size of the secondary grain of the wire produced with the new manufacturing technology is between 6 and 8 per ASTM scale, which is 1 to 2 grades less than the size of the secondary grain of the wire produced with the original MORGAN technology. A microstructural analysis indicates that for both production technologies the ferrite content in the material is between 93 % and 95 % and perlite is between 5 % and 7 %, depending on the carbon content of each heat, in other words, if the carbon content is high the content of perlite is high too. The tensile properties of the hot rolled wires produced with both technologies (old and new) are in accordance with the prescribed values according to the standard EN 10263-2 for the steel C8C. The tensile-strength and yield-strength values for the wires produced with the new technology are lower by 12 MPa to 21 MPa in comparison with the wires produced with the old technology. The values for the elongation and reduction of the area of the wires produced with the new technology are higher by 2.8 % to 4.8 % in comparison with the wires produced with the old technology.[7,8]

3 RESULTS AND DISCUSION

The testing of the steel plasticity in industrial conditions was carried out with a compression test in the cold state on the samples with a height of $h_o = 1.5d_o$ (d_o – diameter of a rolled wire). The final height was one-third of h_o.

The estimation of the sample surfaces after cold compression was conducted by using a rating of 0 to 3, where the ratings of 0 and 1 indicated a satisfactory surface and the ratings of 2 and 3 an unsatisfactory one. The shallow grooves that occur as rolling scars as well as the typical fiber surface cracks that mostly appeared on the test samples with a surface estimation of 0 and 1 are not considered as surface defects. The results of the estimation of the tested samples' surface condition after the cold compression for the old and new manufacturing technologies are given in **Table 2**. The test results clearly indicate that the ability for cold forming of the wires produced with the new technology increased much more than the ability of the wires produced with the old manufacturing technology.

The compression test at room temperature in the laboratory conditions was carried out on a SINTECH 10/D (USA) tester at the Polytechnic University of Turin. We tested the rolled wires with a diameter of 12 mm made from the heats 350871 and 350866. The chemical compositions of these heats are given in **Table 3**.

Table 2: Summary review of the estimation of the sample surfaces after the cold compression test of the rolled wires with the diameters of 6 mm to 12 mm, produced with the old and new technologies
Tabela 2: Pregled ocene površine po hladnem stiskanju valjane žice s premerom od 6 mm do 12 mm, izdelane po stari in novi tehnologiji

Techno-logy	Number of rolled coils for plasticity testing	Estimation of the sample surface after the cold compression test (n_0, n_1, n_2, n_3)/%								Sum of the coils with the plasticity estimation of 0 and 1		Sum of the coils with the plasticity estimation of 2 and 3	
		0		1		2		3					
		n_0	%	n_1	%	n_2	%	n_3	%	$n_0 + n_1$	%	$n_2 + n_3$	%
Old	509	71	13.9	113	22.2	127	24.9	198	38.9	184	36.2	325	63.8
New	581	306	53.2	251	47.7	14	2.4	10	1.7	557	95.9	24	4.1

Note: n_0, n_1, n_2, n_3 are numbers of defect classification

Table 3: Chemical compositions of the tested heats
Tabela 3: Kemijska sestava preizkušanih talin

Heat	C	Si	Mn	P	S	Cu	Cr	Ni	Al	N
	w/%									
350866	0.07	0.05	0.39	0.015	0.013	0.06	-	0.02	0.047	0.0114
350871	0.08	0.05	0.38	0.010	0.012	0.06	0.02	0.02	0.047	0.0112

The original height of the tested samples was h_o = 24 mm. It means that the ratio between the original height and the diameter ($h_o = 2d_o$) was not standardized. The cold compression was carried out in four compression degrees and at two deformation speeds (0.5 mm/s and 1.0 mm/s). All the relevant parameters of the process that were measured or calculated are shown in **Tables 4** and **5**. These tables give the estimations of the tested sample surfaces according to the accepted criterions for industrial conditions with the aim of achieving estimation coherence.[7]

The degree of deformation is calculated according to the following equation:

$$\varphi = \ln\left(\frac{h_0}{h}\right) \tag{1}$$

where h_o is the original height of a sample before the compression, h is the height of a sample after the compression.

The resistance of steel to deformation is calculated according to the following equation:

$$k_f = \frac{F \cdot h}{A_0 \cdot h_0}\left(\frac{N}{\mathrm{mm}^2}\right) \tag{2}$$

where F is the compression force (N), A_o is the original cross-section of a tested sample before the compression.

The results of the plasticity testing conducted on the nonstandard samples ($h_o = 2d_o$) at room temperature and with different degrees and rates of deformation indicate that the low-carbon steel, which deoxidized due to aluminum and was produced with the new thermomechanical process on the MORGAN wire rolling mill, is very plastic (**Tables 4** and **5**). We observed and recorded the defects with the ratings of 0 or 1, but the 0 rating is the dominant surface-condition estimation. At the compression-tool speed of 0.5 mm/s, which is the standard requirement, the 0 rating was recorded for the third and fourth deformation degrees, and at the tool speed of 1.0 mm/s, which is a nonstandard requirement, it was determined that the surface condition rating of 0 related to the second and third deformation degrees, while rating 1 related to the fourth degree of deformation. The ratings

Table 4: Results of the compression testing at room temperature of the wires with a diameter of 12 mm from the heat 350866 for the testing speeds of 0.5 mm/s and 1.0 mm/s
Tabela 4: Rezultati stiskanja pri sobni temperaturi za žico premera 12 mm iz taline 350866 pri hitrostih preizkusa 0,5 mm/s in 1,0 mm/s

Sample number	Average compression force	Reduction of height	Compression speed	Time of compression	Deformation rate	Degree of deformation	Average resistance to deformation	Surface estimation after compression [Exist (+), Nonexist (–)]			
	F/N	Δh/mm	v/(mm/s)	t/s	$\dot{\varphi}$/s^{-1}	φ	k_f/(N/mm^2)	0	1	2	3
1.1–4.1	69519	4	0.5	8	0.1823	2.279×10^{-2}	512.2	–	–	–	–
1.2–4.2	103039	8	0.5	16	0.4055	2.534×10^{-2}	607.4	–	–	–	–
1.3–4.3	140591	12	0.5	24	0.6931	2.888×10^{-2}	621.5	+	–	–	–
1.4–4.4	218922	16	0.5	32	1.0986	3.433×10^{-2}	645.2	+	–	–	–
1.5–4.5	71785	4	1.0	4	0.1823	4.557×10^{-2}	528.9	–	–	–	–
1.6–4.6	105292	8	1.0	8	0.4055	5.068×10^{-2}	621.0	+	–	–	–
1.7–4.7	142252	12	1.0	12	0.6931	5.776×10^{-2}	628.9	+	–	–	–
1.8–4.8	224235	16	1.0	16	1.0986	6.866×10^{-2}	660.9	–	+	–	–

Table 5: Results of the compression testing at room temperature of the wires with a diameter of 12 mm from the heat 350871 for the testing speeds of 0.5 mm/s and 1.0 mm/s

Tabela 5: Rezultati stiskanja pri sobni temperaturi za žico premera 12 mm iz taline 350871 pri hitrostih preizkusa 0,5 mm/s in 1,0 mm/s

Sample number	Average compression force	Reduction of height	Compres-sion speed	Time of compression	Deformation rate	Degree of deformation	Average resistance to deformation	Surface estimation after compression [Exist (+), Nonexist (–)]			
	F/N*	Δh/mm	v/(mm/s)	t/s	$\dot{\varphi}$/s^{-1}	φ	k_f/(N/mm^2)	0	1	2	3
1.1–4.1	71431	4	0.5	8	0.1823	2.279 ×10^{-2}	526.3	–	–	–	–
1.2–4.2	104098	8	0.5	16	0.4055	2.534 ×10^{-2}	613.9	–	–	–	–
1.3–4.3	141983	12	0.5	24	0.6931	2.888 ×10^{-2}	627.6	+	–	–	–
1.4–4.4	221047	16	0.5	32	1.0986	3.433 ×10^{-2}	651.5	+	–	–	–
1.5–4.5	72764	4	1.0	4	0.1823	4.557 ×10^{-2}	536.3	–	–	–	–
1.6–4.6	106957	8	1.0	8	0.4055	5.068 ×10^{-2}	630.5	+	–	–	–
1.7–4.7	143398	12	1.0	12	0.6931	5.776 ×10^{-2}	633.9	+	–	–	–
1.8–4.8	227316	16	1.0	16	1.0986	6.866 ×10^{-2}	669.9	–	+	–	–

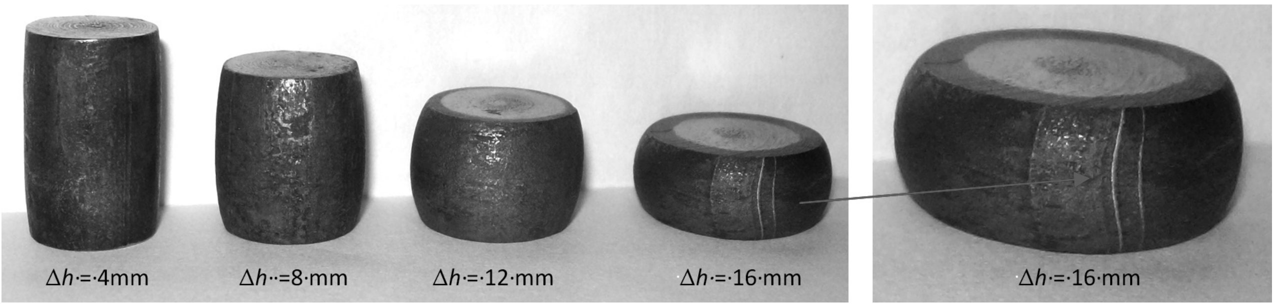

Figure 1: Surfaces of cold compressed specimens of the wire with a diameter of 12 mm from the heat No. 350866 (surface-defect rating 1 after the fourth degree of deformation, Δh = 16 mm, the tool speed of the testing machine is 1 mm/s)

Slika 1: Površina hladno stisnjenih vzorcev žice premera 12 mm iz taline št. 350866 (površinska napaka, označena z 1 po četrti stopnji deformacije, Δh = 16 mm, hitrost orodja na preizkusnem stroju 1mm/s)

of 0 and 1 relate to small, shallow surface defects resulting from the rolling scars (**Figure 1**).

4 CONCLUSION

The new thermomechanical rolling process on the MORGAN wire rolling mill, applied to the low-carbon steel C8C, provides a better grain-boundary migration, set with Zener's criteria, during the heating process and during the dynamic and static recrystallization, that is, the coarsening of the austenite grains and, consequently, the growth of the secondary grains. Also, the precipitates of aluminum nitride have a tendency towards Ostwald ripening. The coarser aluminum nitride precipitates, which have no coherent link with the matrix, are lower barriers to the movement of dislocations during the plastic deformation due to the Orowan mechanism. This, in combination with the coarser secondary structure, taking into account the Hall-Petch equation, ensures lower values of the upper yield stress and a lower deformation resistance and high ductility of the steel C8C wire in the cold state.

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