ANALYSIS OF THE EFFEC OF THE ASYMMETRIC ROLLING PROCESS ON THE DEVELOPMENT OF THE MICROSTRUCTURE OF LOW-CARBON STEELS WITH MICRO-ADDITIVES

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Abstract

The paper presents the results of the outer surface quality examinations of Zr-1%Nb alloy tubes after the process of pilger rolling with a deformation of $\varepsilon=72\%$ on a KPW rolling mill. For the analysis of the effect of the strain rate and the degree of deformation of the magnitude of the yield stress σ_p of the investigated alloy, an experiment was programmed based on the industrial conditions and physical modelling of the rolling process was carried out. For the physical modelling of the process under examination, the GLEEBLE 3800 metallurgical process simulator was employed. Based on the examination results, the relationship $\sigma_p= \sigma_p(\varepsilon, \acute{\varepsilon})$ has been obtained for discontinuous cold deformation conditions and recommendations for the division of the strain distribution over the deformation zone length have been given.

Keywords: Numerical modelling, physical modelling, asymmetric rolling, micro-additive low-carbon steels

INTRODUCTION

The discovery of new gas deposits in Poland and in the world has caused an increase in demand for pipeline tubes made from steel plate by the spiral and longitudinal welding methods. The requirements imposed on steels intended for pipelines are specified in European Standard EN 10208-2 being equivalent to American Standard API 5L. These steels are distinguished by a high yield point, high tensile strength and good weldability resulting from the reduced carbon content. To enhance the mechanical and plastic properties, micro-additives, such as V, Ti, Mn and Mo, are introduced to the steel. These micro-additives inhibit also the growth of austenite grains [1÷3]. The technology of pipeline plate production from those steel grades is relatively complex. Heating prior to the rolling process must be conducted in a manner that prevents excessive austenite grain growth (normally in the temperature range of 1150÷1200°C). The assurance of high plastic and mechanical properties is only possible owing to a well developed rolling technology. Introducing asymmetric deformation conditions between the upper and lower rolls to the rolling process causes zones of oppositely oriented tangential stresses to occur in the metal. Such a deformation state has a grain-refinement effect in the rolled band. These conditions cause, that rolling process with so-called double asymmetry can included to intensive plastic working processes [4, 5].The occurrence of zones in which friction forces on the upper and the lower roll are oppositely oriented is advantageous to the rolling process, as their effect can be compared to the action of tension and back tension forces. This reduces the total roll separating force, thanks to which it will be possible to apply larger single reductions, which will also contribute to the refinement of the austenite structure [6, 7]. The application of asymmetry in the rolling process results also in a smaller elastic deflection of the rolling stand. Thanks to this it is possible to use smaller working roll deflection forces and to obtain finished plate with smaller dimensional deviations across the length and width of the band. However, asymmetry introduced to the rolling process causes the band to band to bend on exit from the roll gap and also results in an increase in the total rolling moment and an uneven distribution of torques between the working rolls, which may result in an overloading of the rolling mill's drives with a possible occurrence of slips in the roll bite. A method for the elimination of those adverse phenomena is to introduce simultaneously two types of asymmetry with appropriately selected asymmetry factors to the rolling process.

1. THE AIM, SCOPE AND METHODOLOGY OF THE INVESTIGATION

The primary aim of the undertaken investigation was to establish such values of asymmetry factors and technological rolling process parameters, at which a stress state will occur in the deformation zone, which is favourable to austenite grain refinement and, at the same time, a reduction in energy and force parameters will result. Thanks to the above, it will be possible to use larger single reductions, which will also contribute to a refinement of the austenite structure.

A finite element method-relying program, FORGE®, was employed in the study for numerical modelling of a rolling process with two types of asymmetry. The investigation was conducted on specimens made of an experimental low-carbon steel with micro-additives with a chemical composition developed at the Czestochowa University of Technology's Institute for Plastic Working and Safety Engineering. **Table 1** gives the experimental chemical composition of the steel used for the investigation.

Table 1 Experimental chemical composition of the investigated steel [%]

Chemical composition, %												
C	**Mn**	**Si**	**P**	**S**	**Ni**	**Mo**	**Cu**	**Cr**	**Nb**	**Al**	**Ti**	**N**
0.095	1.95	0.35	0.010	0.010	0.11	0.20	0.12	0.13	0.055	0.032	0.043	36 ppm

Working rolls, each with a diameter of 150 mm, were taken for numerical modelling. Two types of asymmetry were applied in the rolling process. The first type of asymmetry (kinetic) was introduced by differentiating the working roll rotational speeds, where the lower roll had a constant rotational speed of n = 78 rpm, while the upper roll's rotational speed was reduced. The second type of asymmetry (geometric) was introduced by differentiating the working roll diameters (the upper roll had a constant diameter, while the diameter of the lower roll was reduced). The asymmetry factors for both kinetic and geometric asymmetries were identical, being $a_v=a_d=1.10 \div 1.30$. The rolled band temperature was t = 880°C. The range of applied reductions was $\varepsilon_w = 0.1 \div 0.5$. The numerical simulations were carried out for a band with an initial height of $h_0=10$ mm (a roll diameter ratio of $h_0/D = 0.067$). The following data were adopted for the simulations: ambient temperature, 20°C; tool temperature, 60°C; friction factor, 0.7; friction coefficient, 0.3; the coefficient of heat exchange between the material and the air, $\alpha_{pow} = 10$ [W/Km^2]; and the coefficient of heat exchange between the material and the tool, $\alpha_{narz} = 3000$ [W/Km^2].

To perform simulation of plastic working processes, where the finite element method is used, it is necessary to well know the characteristics describing the rheological properties of the steel in the form of stress-strain diagrams, which consider the effect of band temperature and strain rate. To this end, plastometric tests using the GLEEBLE 3800 simulator were carried out for the investigated steel grade. Based on the tests, diagrams of the relationship of steel stress versus strain were drawn and the coefficients of the flow stress function were selected (**Table 2**), which were used in computer simulations of the rolling process. For the description of the flow stress σ_p as dependent on the deformation parameters, the Henzel and Spittel functions in the form of the following relationships were used (1):

$$\sigma_p = Ae^{m_1 T} \varepsilon^{m_2} \dot{\varepsilon}^{m_3} \varepsilon^{\frac{m_4}{\varepsilon}} (1+\varepsilon)^{m_5 T} \varepsilon^{m_7 \varepsilon} \dot{\varepsilon}^{m_8 T} T^{m_9} \qquad (1)$$

where: σ_p - flow stress, T - band temperature, ε - actual strain, $\dot{\varepsilon}$ - strain rate, A, $m_1 \div m_9$ - function coefficients.

Table 2 The values of parameters A and $m_1 \div m_9$ employed for the determination of the σ_p of the steel used for for the investigation

Wartości parametrów uzyskanych w wyniku aproksymacji równania								
A	*m₁*	*m₂*	*m₃*	*m₇*	*m₄*	*m₅*	*m₈*	*m₉*
4.58107E-09	-0.007537304	0.386415	-0.052943	-0.137999	-0.000198	-0.001184	0.000151	4.736197

2. ANALYSIS OF THE INVESTIGATION RESULTS

Table 3 gives the results of numerical and experimental tests obtained during rolling the investigated steel at a temperature of 1160°C.

Table 3 Results of the experimental tests of the rolling process

	Specimen	h_0 [mm]	Relative strain ε_w [%]	Total pressure force [kN] Forge	Pressure force [kN] Extensometr 1	Pressure force [kN] Extensometr 2	Total pressure force [kN]	Error	1/bend radius [1/m] Forge	1/bend radius [1/m] Lab	Error
symmetry V_d=V_g; D_d=D_g	P1	10	10%	21.38	11.52	11.87	23.39	0.086	0	0	
	P2	10	15%	30.21	16.91	16.42	33.33	0.103	0	0	
	P3	10	25%	45.91	22.95	24.78	47.73	0.040	0	0	
speed asymmetrya_v = 1.1	P4	10	10%	22.76	11.38	12.40	23.78	0.049	1.65	1.98	0.20
	P5	10	15%	31.00	15.50	16.74	32.24	0.040	2.15	2.56	0.19
	P6	10	25%	45.91	22.95	24.78	47.73	0.039	2.96	3.58	0.21
double asymmetry a_d=1.1; a_v=1.10	P7	10	10%	19.82	9.91	11.01	20.92	0.055	0	0	
	P8	10	15%	28.45	14.23	15.65	29.88	0.050	0	0	
	P9	10	25%	43.56	21.78	20.04	41.82	0.039	0	0	

Lab - experimental test results

The data given in **Table 3** show that differentiating the rotational speeds of the working rolls influences both the value of band curvature at the roll bite exit, as well as the band bend direction. For all the analyzed relative strains, ε_w, the band, after leaving the roll gap, bent towards the upper roll (the roll with a lower rotational speed), with the magnitude of the band bend radius increasing with the increase in the value of the applied reduction ε_w. The introduction to the rolling process of two types of asymmetry (kinetic and geometric) with the identical values of the asymmetry factors a_v = a_d yielded a straight band for the entire range of the remaining rolling process parameters (**Table 3**). After applying asymmetric rolling conditions (kinetic asymmetry) with reductions of ε_w = 0.1 and 0.15 in the rolling process, a slight (several percent) increase in the magnitude of the average pressure force p_j resulted. By contrast, increasing the reduction to ε_w = 0.25 in asymmetric rolling with one asymmetry type (kinetic asymmetry) decreased the magnitude of the total pressure force (**Table 3**). Applying two types of asymmetry (kinetic and geometric) in the process of rolling feedstock with an initial height of h_0 = 10 mm caused a reduction in the magnitude of the average pressure force p_j for the entire examined range of relative strain variations, ε_w = 0.10 ÷ 0.25. The greatest drops (by approx. 5%) were observed for the largest reduction magnitude of ε_w = 0.25.

The data given in **Table 3** show that a good agreement was obtained between the numerical simulation results and the laboratory testing results. The calculated error for the results obtained from the laboratory tests for the pressure force ranged from 4 to 10%, while the error calculated for the band curvature amounted to about 20%. The occurred differences between the results obtained during rolling in laboratory conditions and the numerical simulation results were due to the fact that the laboratory conditions deviated from the ideal conditions existing within the FORGE 2011® program in terms of, e.g., friction conditions occurring at the metal-tool contact surface, and the feedstock in actual conditions was covered with a scale layer and its temperature was not uniform within the entire volume.

The observations of the former austenite grain microstructure were conducted on specimen cross-sections using a Nikon Eclipse MA-20 optical microscope. The structure of the starting material is shown in **Figure 1**. Variations in austenite grain size are illustrated in **Figures 2, 4** and **6**.

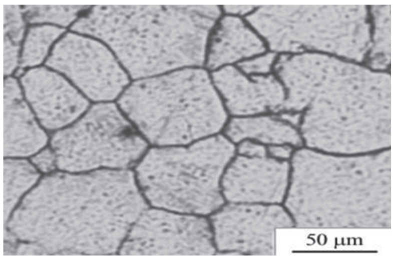

Figure 1 Structure of the material (steel X80) prior to the rolling process; a magnitude of 200x

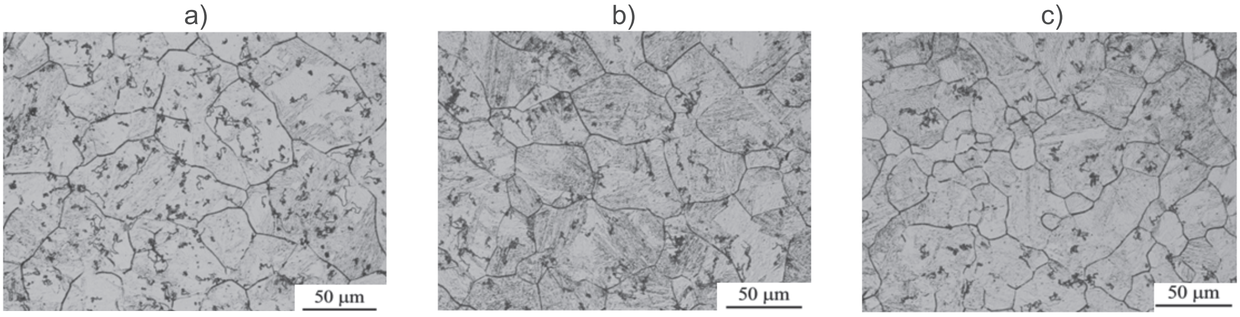

Figure 2 The structure of the steel after deformation with a reduction of ε_w = 0.10; a) after the symmetric rolling process; b) after the process of rolling with one asymmetry type; and c) after the process of rolling with two asymmetry types

Figures 2a, 2b and **2c** show the steel structure obtained from the process of symmetric rolling and the processes of asymmetric rolling with one and two asymmetry types, respectively, with a reduction of ε_w=0.1. Using the secant method, the size of the formed austenite was determined, and the results of these examinations are presented in **Figure 3**. Based on the obtained results it was found that the use of a small reduction (ε_w = 0.1) in the symmetric process caused a slight austenite grain growth up to 57 μm, compared to the structure obtained before rolling (50 μm). The analysis of the distribution of strain intensities for the technological case under consideration (**Figure 2a**) found that the critical strain needed for the initiation of static recrystallization had not been exceeded and the microstructure had only recovered (the absence of oblong grains). For the specimen after the process of rolling with a reduction of $\varepsilon_w = 0.1$ using one type of asymmetry, a slight austenite grain refinement to 46 μm was obtained (**Figure 2b**). The analysis of the distribution of strain intensities determined in the numerical studies showed that the use of a single asymmetry type in rolling with a reduction of $\varepsilon_w = 0.1$ allowed the critical strain to be exceeded and static recrystallization to be initiated upon band exit from the deformation zone. The use of two asymmetry types (**Figure 2c**) in the rolling process resulted in a further increase in strain intensity and austenite microstructure refinement to a value of approx. 40 μm.

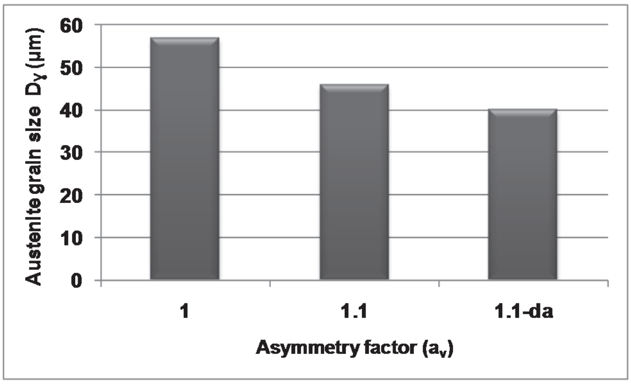

Figure 3 The austenite grain size as determined based on the laboratory tests of rolling plate of the experimental grade of micro-additive low-carbon steel with a reduction of $\varepsilon_w = 0.10$

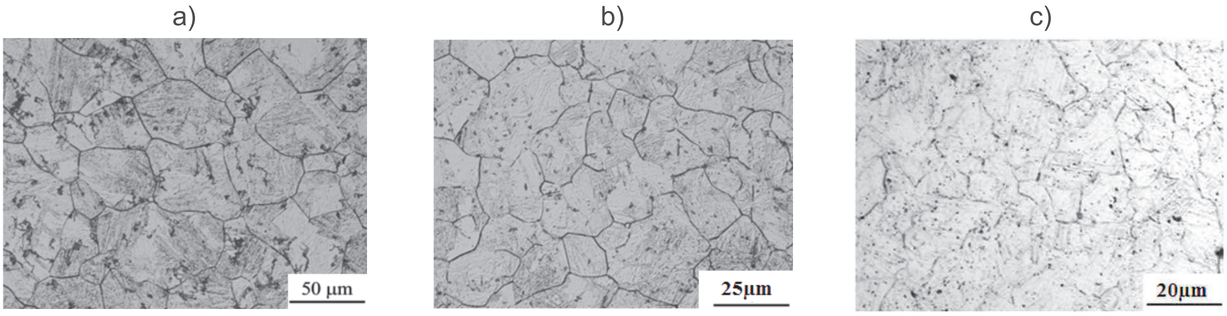

Figure 4 The specimen microstructure after the process of rolling with a reduction of $\varepsilon_w = 0.15$; a) for the symmetric rolling process; b) for the rolling process with a single asymmetry type; c) for the rolling process with two asymmetry types

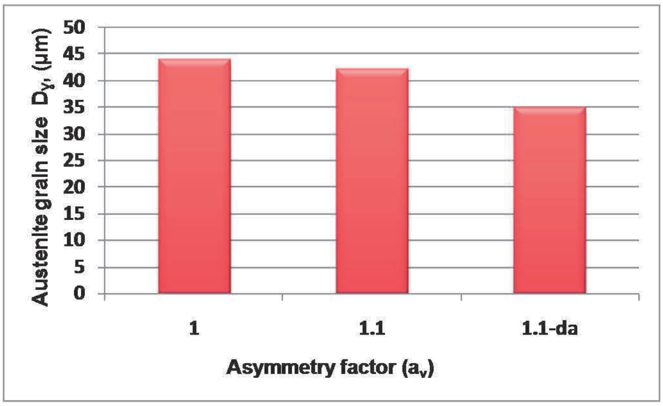

Figure 5 The austenite grain size as determined from the laboratory tests of the process of rolling plate of the experimental micro-additive low-carbon steel with a reduction of $\varepsilon_w = 0.15$

Figures 4a, 4b and **4c** show the microstructure of specimens after the processes of symmetric rolling and asymmetric rolling (with one and two asymmetry types, respectively) with a reduction of ε_w=0.15. Using the secant method, the average austenite grain size was determined to be 44 μm for the specimen after the symmetric rolling process, 42 μm for the specimen after the process of rolling with one asymmetry type, and 35 μm for the specimen rolled with two asymmetry types (**Figure 5**). Based on the tests carried out it was found that after each of the rolling process variants used the former austenite grain size had been refined. The distribution of strain intensities obtained from the numerical simulations for the processes of rolling with one and two types of asymmetry showed that after the application of the reduction of ε_w=0.15, static recrystallization had completely occurred. The best results were obtained from the process of rolling with two asymmetry types, as austenite grain refinement to a value of 35 μm had taken place.

Figures 6a, 6b and **6c** show the specimen microstructure obtained after the process of symmetric rolling and after the processes of asymmetric rolling with one and two asymmetry types, respectively, with a reduction of ε_w=0.25. Using the secant method, the average former austenite grain size (**Figure 7**) was determined to be 32 μm after the symmetric rolling process, 28 μm after the process of rolling with one asymmetry type, and 25 μm after rolling with two asymmetry types.

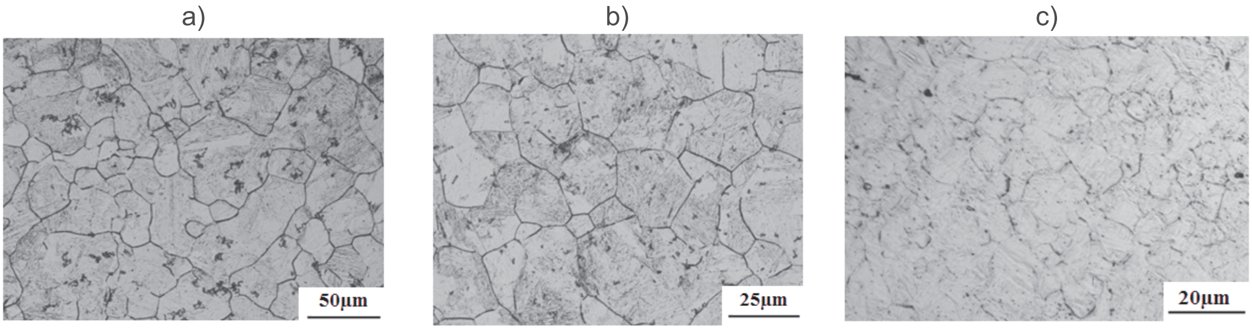
a) b) c)

Figure 6 The specimen microstructure after the process of rolling with a reduction of ε_w = 0.25; a) for the symmetric rolling process; b) for the rolling process with a single asymmetry type; c) for the rolling process with two asymmetry types

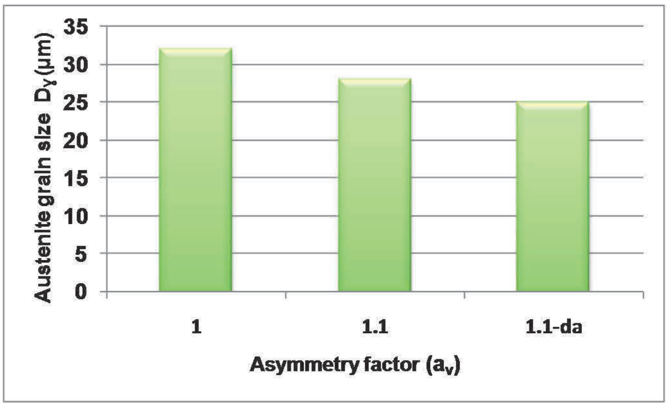

Figure 7 The austenite grain size as determined based on the laboratory tests of rolling plate of the species from experimental low-carbon steel with micro-additives ε_w = 0.25

Using the reduction of ε_w = 0.25 for each of the rolling process variants contributed to an increase in strain intensity and thereby to a reduction of the former austenite grain and, in addition, enabled static recrystallization to take place. The finest grain of about 25 μm was obtained in the specimen from the process of rolling with two types of asymmetry.

3. CONCLUSIONS

Based on the results of the numerical and physical modelling of the process of asymmetric rolling of plates of low-carbon steels with micro-additives, the following conclusions have been drawn:

- the introduction of the sole kinetic asymmetry to the rolling process causes the band to bend towards the upper roll for the entire examined range rolling process parameters;
- by using both the kinetic and geometric asymmetries in the rolling process, a straight band can be obtained for all the examined cases;
- in the case of using the kinetic asymmetry in the rolling process for small reduction values ($\varepsilon_w = 0.10$ and 0.15), a slight (several percent) increase in the value of the average pressure force p_j is obtained, while for a reduction of $\varepsilon_w = 0.25$, a decrease by a few percent;
- the introduction of the kinetic and geometric asymmetry to the rolling process causes a reduction of the average pressure force p_j for the entire examined range of rolling parameters;
- the introduction of the kinetic as well as the geometric asymmetry to the rolling process has the effect of refining the structure of the rolled material as compared to its initial state, which is the higher, the larger the unit reduction is used.

Based on the obtained results of the theoretical studies and experimental tests of the process of asymmetric rolling of micro-additive low-carbon steel plates it can be stated that the simultaneous introduction of the geometric and kinetic asymmetry has an advantageous effect on the stress and strain states, which yields a finished product with a refined structure, while reducing the levels of energy and force parameters.

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