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INFLUENCE OF LONGITUDINAL COLD ROLLING ON THE SURFACE TOPOGRAPHY OF LOW CARBON STRUCTURAL STEEL

Veronika Szarková, Jan Valíček, Martin Vlado, Marta Harničárová, Krzysztof Rokosz, Miloslav Lupták, Ivan Samardžić, Dražan Kozak, Sergej Hloch

Preliminary notes
The paper presents a method of surface evaluation of steel strips formed by longitudinal cold rolling, carried out by a rolling mill DUO 210 SVa. The experiments were performed on samples of low carbon structural steel in order to determine the impact of grain size of material with respect to technological parameters, particularly with respect to a rolling reduction and rolling force. Surface roughness of the steel strips was measured at three locations by an optical profilometer MicroProf FRT. These results were consequently mutually compared.

Keywords: *cold rolling, rolling force, rolling reduction, surface topography*

Utjecaj uzdužnog hladnog valjanja na topografiju površine niskougljičnog konstrukcijskog čelika

Prethodno priopćenje
U radu je prikazana metoda procjene površine ploče formirane uzdužnim hladnim valjanjem, obavljenim pomoću valjaoničkog stana 210 DUO SVa. Izvedeni su pokusi na uzorcima niskougljičnih konstrukcijskih čelika, kako bi se utvrdio utjecaj dimenzije zrna materijala s obzirom na tehnološke parametre, a posebice s obzirom na redukciju valjanja i silu valjanja. Hrapavost površine ploča mjerena je na tri mjesta optičkim profilometrom MicroProf FRT. Zbog toga su ovi rezultati međusobno uspoređeni.

Ključne riječi: *hladno valjanje, redukcija valjanja, sila valjanja, topografija površine*

1 Introduction

Rolling is a continuous process in the course of which the material being formed deforms between the working rolls under conditions of the prevailing all-around pressure. This process is related to a reduction in height during rolling, therefore to the extension of a tensile strip of the given width and thickness. Rolled strips are delivered from the rolling mills at a certain speed, which changes during rolling [1 ÷ 13]. Continual cold rolling is an important process in metallurgical industry. Its performance directly affects the quality of the final product. This process is a very complex system including also a number of multi-disciplines such as: computing technique, automatic control, mechanics, material engineering and more. Any well designed system renovation can bring a financial benefit for a company regarding improvement of the performance, quality and overall business competitiveness [1 ÷ 13]. The main goal of metallurgical processes is to search for the shortest, most economical, environmentally friendly and sustainable way to transform raw materials into the final products [14 ÷ 15].

2 Experiments

The experiment was carried out in order to monitor the impact of the main technological parameters on the surface topography, especially in relation to the reduction Δh. In the framework of the experiment, the following parameters were measured: rolling force, reduction in thickness, grain size, surface roughness of the rolled product. Correlation interrelationships were derived and an interactive mathematical model was created.

2.1 Original material

The initial material used in this experiment was low carbon structural steel of type PN EN 10263-2:2004 with the tensile strength R_m of 370 MPa and the yield strength $R_{p0,2}$ of 225 MPa. The original size of a sample was 72 × 33 × 1,6 mm. The chemical composition of the steel strips is shown in Tab. 1.

Table 1 Chemical composition of low carbon steel / wt. %

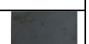
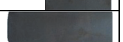
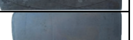
Fe	C	Mn	Si
99,639	0,023	0,193	0,012
P	S	Cr	V
0,008	0,005	0,021	0,002
Cu	Al	Co	As
0,028	0,056	0,008	0,005

Chemical analysis was performed by a glow discharge optical emission spectrometer LECO GDS 750.

2.2 Plastic deformation

The metal is considered to deform plastically during rolling process. There were made four rolling stocks with different reductions in accordance to the technological parameters listed in Tab. 2.

Table 2 Technological parameters of the created samples

Steel strips marking	h_0 / mm	h_1 / mm	Δh / mm	Picture
a	1,6	1,6	-	
b	1,6	1,2	0,4	
c	1,6	1,1	0,5	
d	1,6	1,0	0,6	
e	1,6	0,8	0,8	

The steel strips b, c, d, e were rerolled by the rolling mill DUO 210 SVa at a speed of rolls v_{roll} = 42 m/min.

A cylinder diameter is of 210 mm and the cylinder surface roughness is of 0,4 µm. The original sample marked "a" was not rerolled due to a mutual comparison of samples.

3 Results and discussion

3.1 Results from the optical profilometer MicroProf FRT

The steel strips produced by longitudinal cold rolling were measured at three different positions by the optical profilometer MicroProf FRT. Fig. 1 shows the different surface topography measurement positions due to different deformation of the material. The first area of the surface topography measurement is called an entrance area as the steel strip enters the rolling mill. The second area is in the middle part of the material and the third area is the lower part of the material. 3D surface topography for the measured areas was obtained by the optical profilometer.

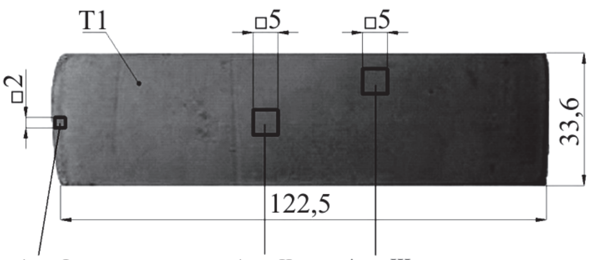
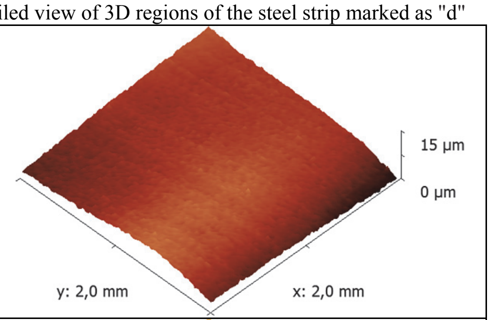
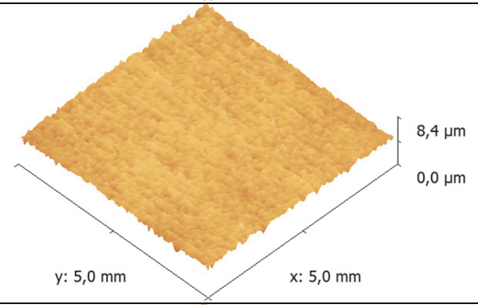
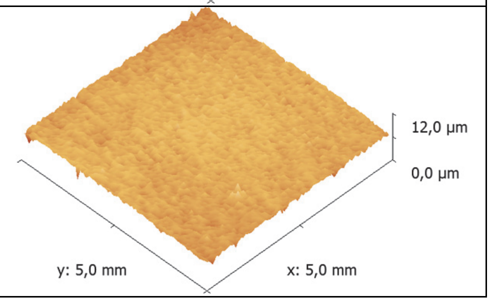


Figure 1 Illustration of area topography measurement with a reduction in thickness of 0,6 mm

Table 3 Detailed view of 3D regions of the steel strip marked as "d"

Area I	
Area II	
Area III	

The data measured by the optical profilometer MicroProf FRT were analyzed by the program Gwyddion. By means of this program were obtained the data on surface irregularities of the steel strips at the measured areas. In Tab. 3, there is a detailed view of 3D regions of the steel strip marked as "d" with a reduction in thickness of 0,6 mm.

Information on surface irregularities produced by longitudinal cold rolling for individual reductions in thickness Δh, mean arithmetic deviation of the surface profile Ra, root mean square deviation of the profile Rq, and the greatest height of profile parameter Rz are given in Tab. 4.

Table 4 Appropriate standardized parameters of the surface texture evaluation for each sample and area

	Steel strips marking	a	b	c	d	e
	Δh / mm	-	0,40	0,50	0,60	0,80
Area I	Ra / µm	-	0,34	0,30	0,17	0,22
	Rq / µm	-	0,47	0,41	0,22	0.30
	Rz / µm	-	3,00	2,67	1,39	2,31
Area II	Ra / µm	0,71	0,37	0,43	0,21	0,12
	Rq / µm	0,97	0,52	0,56	0,28	0,17
	Rz / µm	7,42	3,40	3,77	2,05	1,60
Area III	Ra / µm	0,70	0,41	0,38	0,23	0,16
	Rq / µm	0,95	0,56	0,55	0,32	0,22
	Rz / µm	7,16	3,63	5,17	2,29	2,04

On the basis of the collected data (Fig. 2) a chart was created, which shows the best quality (the lowest values of the mean arithmetic deviation of the surface profile parameter Ra) of the steel strips in the first region, except for the steel strip marked "e", but the highest roughness (the highest values of the mean arithmetic deviation of the surface profile parameter Ra) of the steel strips was achieved in the third measured area, except for the steel strip marked "c". The surface roughness in implicit expression is given as follows: $Ra = f(F_{roll}, Q_{Froll}, b_s, v_{roll}, n_{roll})$. Therefore it is necessary to search for the links between the technology and the final quality of the surface.

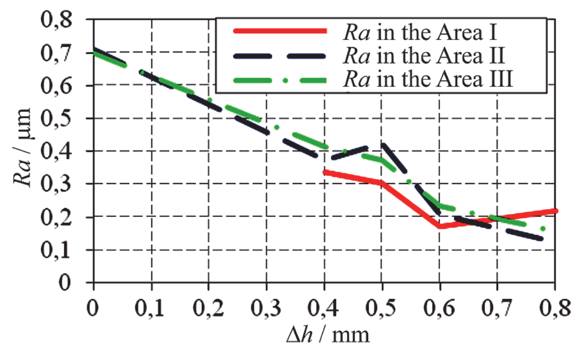


Figure 2 Graphical illustration of the arithmetic mean deviation of the surface at three measuring regions

Using the Gwyddion program, the measured areas of individual samples were analyzed. The measured areas were divided into 10 equidistant measuring lines with a distance of 0,2 mm in the first area for the steel strips a, b, c, d with the dimensions of 2 × 2 mm (see Fig. 1) and for the steel strip "e" with the dimensions of 4,5 × 4,5 mm with a step of 0,45 mm, in the second and the third region with the dimensions of 5 × 5 mm with a step of 0,5 mm. The measuring lines were perpendicular to the rolling direction. From each measuring line, a signal was obtained bearing information about the distribution of surface elevation fluctuations (Fig. 3).

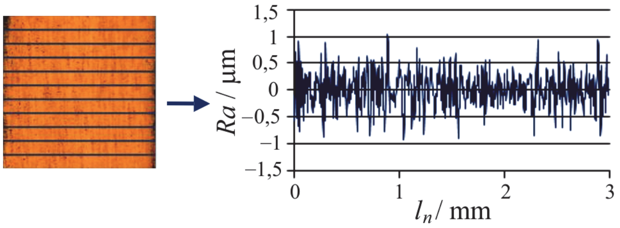


Figure 3 The measured regions on the sample with the reduction in thickness of 0,6 mm in 10 equidistant lines with a distance of 0,5 mm from which the signals of the surface roughness were obtained

3.2 Link between the reduction in thickness Δh, surface roughness Ra and rolling force F_{roll}

The surface quality can be demonstrated through the used force when rolling that is defined as a vertical component of the resultant force or as the load with which the rolls act on the metal. In this case, the values in the first area ranged from 65,55 kN to 90,07 kN, and were calculated by the formula

$$F_{\text{roll}} = R_{\text{p0,2}} \cdot S_{\text{h}} \cdot Q_{F\text{roll}}, \quad (1)$$

and

$$Q_{F\text{roll}} = \frac{l_{\text{d}}}{h_{\text{s}}} = \frac{2 \cdot \sqrt{R \cdot \Delta h}}{h_1 + h_0}. \quad (2)$$

Tab. 5 gives the parameters for calculation of the rolling force F_{roll} and forming factor $Q_{F\text{roll}}$. The forming factor characterizes the influence of the mean stress acting on the surface of contact between the rolled metal and the roll on the size of the rolling force. The rolling factor has an integrated character in terms of material stress intensity with an impact on the performance of the rolling mill (the ratio of mass to time), economy of process (the ratio of currency to mass) and therefore on the rolling speed v_{roll} [16 ÷ 17].

Table 5 Parameters for calculation of the rolling force F_{roll} and forming factor $Q_{F\text{roll}}$

Steel strips	Δh / mm	l_{d} / mm	h_{s} / mm	S_{h} / mm^2	$Q_{F\text{roll}}$ / −	F_{roll} / kN
a	-	-	-	-	-	-
b	0,4	12,96	2,8	216,13	4,63	65,55
c	0,5	14,49	2,7	240,92	5,37	72,91
d	0,6	15,88	2,6	264,31	6,11	82,71
e	0,8	18,33	2,4	303,37	7,64	90,07

The greater rolling force is used, the greater the reduction in thickness and smoother surface of the rolled stocks is achieved (Fig. 4).

By the algorithm a relationship was also found between the grain size D_{grc} and the reduction in thickness Δh (Fig. 5).

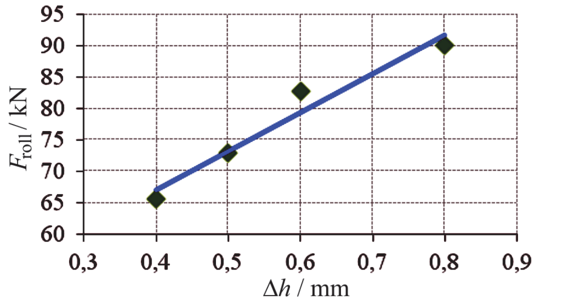


Figure 4 Relation between the rolling force F_{roll} and the reduction in thickness Δh

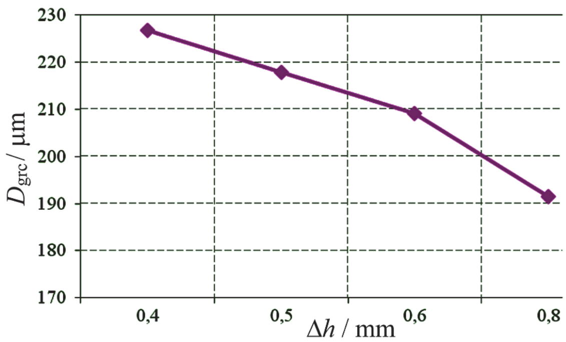


Figure 5 Relation between the grain size D_{grc} and the reduction in thickness Δh

4 Analytical processing

For the purpose of analytical processing and generalisation, the authors have chosen the concept of regression and correlation analysis. In order to determine the main functions of the rolling process a number of metallic materials was measured with different mechanical parameters. As a reference parameter was chosen the modulus of elasticity and the material constant of plasticity K_{plmat} (3) used in previous works of the authors.

$$K_{\text{plmat}} = \frac{10^{12}}{E_{\text{mat}}^2}. \quad (3)$$

It was found that using the index ratio (4) that is incorporated into the regression relations for reduction in thickness, it is possible to distinguish different materials in the process of rolling.

$$I_{\text{kpl}} = \sqrt{\frac{K_{\text{plmat0}}}{K_{\text{plmat}}}}. \quad (4)$$

Based on this finding, an algorithm for mathematical modelling in MATLAB has been developed. An example of the course of basic parameters for rolling of the material PN EN 10263-2 is shown in Fig. 6. A set of equations for the algorithm (1) and Fig. 6 contain the following variables:

n_{roll} − rotation of the rolls, rev/min
E_{mat} − modulus of elasticity, MPa
F_{roll} − rolling force, kN
D_{grc} − grain size, mm
Ra_{rollm}, Ra_{rollc} − measured and calculated surface roughness, µm

Q_{Froll} − forming factor, −
σ_s − surface tension, MPa
v_{roll} − rolling speed, m/min
S_h − horizontal projection of the contact surface between the rolled metal and the roll, mm^2
h_s − average value of reduction in thickness, mm
l_d − lenght of deformation, mm
Δh − reduction in thickness, mm
b_s – cylinder working width, mm.

The equations are calculated according to the algorithm (1) given below.

Algorithm (1):
Droll = 0.210; *Δh* = 0.01:0.01:8; *Kplmato* = 35.7707;
Ementry = 125580, *Emat* = *Ementry*; *bs* = 33; *Kplmat* = 10.^12/1./*Ementry*.^2,
vroll = 148.0662 -132.41266.*(Δ*h* * *Ikpl*) + 160.17705.*(Δ*h* * *Ikpl*).^2 −83.55556.*(Δ*h* * *Ikpl*).^3;
Froll = 43.63183 + 329.16274.*(Δ*h* * *Ikpl*) −413.33298.*(Δ*h* * *Ikpl*).^2 + 222.8675.*(Δ*h* * *Ikpl*).^3;
Rarollc = 1.47963 -0.534 .* (Δ*h* * *Ikpl*);
Qfroll = 0.57873 + 2.50374.*(Δ*h* * *Ikpl*) −3.00062.*(Δ*h* * *Ikpl*).^2 + 1.78554.*(Δ*h* * *Ikpl*).^3;
σ_s = 4.66667E-5 + 354.26751 .* (Δ*h* * *Ikpl*);
nroll = *vroll* /1./(3.14.*Droll*);
Dgrc = 0.05*(0.34843 + 3.30751 .* *Rarollc*);
Sh = 1000**Froll*/1./(*Emat*^0.5.**QFroll*);
ld = *Sh*/1./*bs*;
hs = *ld*/1./*QFroll*.

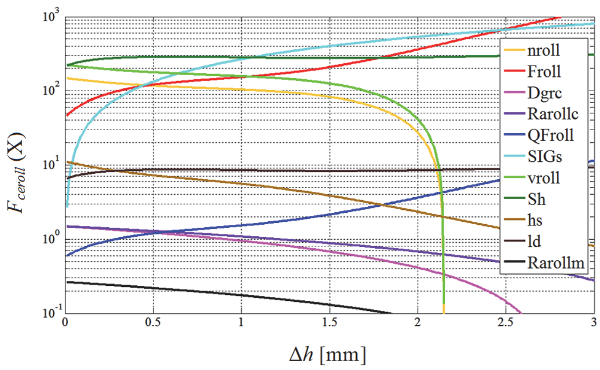


Figure 6 The course of the rolling functions obtained from the algorithm in common logarithms

The following Fig. 6 illustrates the course of rolling functions, showing a high degree of conformity with the measured values given in Tab. 5 and in Fig. 2 and Fig. 4 according to individual reductions up to 0,8 mm. There is a growing difference in the distribution of the measured and predicted values of average roughness (Ra_{rollm}, Ra_{rollc}) = $f(\Delta h_i)$. The theoretical (predicted) roughness decreases more slowly for higher values of the rolling reductions. This is related also to a slow decrease of the structural grain size. This would mean that for large - thickness rolled steel sheets there is a practical limit of the reduction of about 1,6 mm. For the current material there is a theoretical limit value Δh_{lim} of 2,2 mm. It is practically possible to select the reduction in thickness Δh of 2 mm. However increasing the rolling reduction in thickness causes a reduction in rolling velocity, or lies in reduction of rotation of the rolls, followed by a decrease in performance and increase in rolling forces. There are at least two reasons for differences in surface roughness parameters and values of the maximum reduction in thickness. And this can be due to a systematic error in measurement Ra_{rollm} or is caused by a constant and relatively low rolling speed v_{roll} = 42 m/min. The model calculation requires both the rolling speed v_{roll} control and rotation of the rolls n_{roll} control depending on the increase in these parameters: thickness reduction Δh_i, rolling force F_{roll}, surface strengthening σ_s and forming factor Q_{Froll}.

5 Conclusions

The paper presents the results obtained from the surface topography produced by cold rolling of low carbon structural steel PN EN 10263-2:2004. The presented results show the relation between the rolling force F_{roll}, the individual reduction in thickness Δh and the surface roughness Ra of the rolling mill DUO 210 SVa. There were selected the main parameters of cold rolling and also derived the functional dependencies of these parameters in relation to the reduction in thickness Δh. The generalisation to the reference material and algorithm (1) using the ratio I_{kpl} according to the formula (4) gives the possibility of mathematical modelling of the rolling process at an early stage of designing and performing interactive adjustments for improvements and the control of technological regime of rolling of materials with different mechanical properties. The working algorithm and model solution has been derived from the results of measurements using the rolling mill DUO 210 SVa. This has been succesfully verified with no further adjustments. For industrial multistage rolling mills with the reduction in thickness, the presented solution will need to be adjusted. These adjustments for industrial rolling mills will be solved over the period ahead. A set of equations according to the algorithm (1) supplements suitably the existing set of computing functions for cold rolling. It has been found and confirmed that even individual materials in the rolling process can be distinguished using the index $I_{kpl} = f(E_{mat})$. The new conception supplements the procedures and method of check in design. It enables the interactive mathematical modelling of the process according to the freely selected inputs and required outputs for various types of rolled materials at respecting their specific mechanical properties.

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Authors' addresses

Veronika Szarková
Institute of Economics and Control Systems,
Faculty of Mining and Geology,
RMTVC, Faculty of Metallurgy and Materials Engineering,
VŠB - Technical University of Ostrava,
17 listopadu 15, 708 33 Ostrava – Poruba, Czech Republic

Jan Valíček
Institute of Physics, Faculty of Mining and Geology,
RMTVC, Faculty of Metallurgy and Materials Engineering,
VŠB - Technical University of Ostrava,
17 listopadu 15, 708 33 Ostrava – Poruba, Czech Republic

Martin Vlado
Faculty of Metallurgy,
Technical University of Košice,
Letná 9, 040 01 Košice, Slovak Republic

Marta Harničárová
Institute of Physics, Faculty of Mining and Geology,
Nanotechnology Centre
VŠB -Technical University of Ostrava,
17 listopadu 15, 708 33 Ostrava – Poruba, Czech Republic

Miloslav Lupták
Faculty of Metallurgy,
Technical University of Košice,
Letná 9, 040 01 Košice, Slovak Republic

Krzysztof Rokosz
Division of Electrochemistry and Surface Technology,
Koszalin University of Technology,
Racławicka 15-17, PL 75-620 Koszalin, Poland

Ivan Samardžić
Mechanical Engineering Faculty in Slavonski Brod,
J. J. Strossmayer University of Osijek,
Trg Ivane Brlić Mažuranić 2,
35000 Slavonski Brod, Croatia

Dražan Kozak
Mechanical Engineering Faculty in Slavonski Brod,
J. J. Strossmayer University of Osijek,
Trg Ivane Brlić Mažuranić 2,
35000 Slavonski Brod, Croatia

Sergej Hloch
Faculty of Manufacturing Technologies of Technical University of Košice with a seat in Prešov,
Bayerova 1, 080 01 Prešov, Slovak Republic