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STUDY ON THE INFLUENCE OF SHEET STRAIGHTENING PROCESS ON RESIDUAL STRESS DISTRIBUTION, MECHANICAL PROPERTIES AND STRUCTURE OF DEEP-DRAWING STEEL SHEETS

BADANIA WPŁYWU PROCESU PROSTOWANIA BLACH NA ROZKŁAD NAPRĘŻEŃ WŁASNYCH, WŁAŚCIWOŚCI MECHANICZNE I STRUKTURĘ BLACH ZE STALI GŁĘBOKOTŁOCZNYCH

The article describes the impact of the stretch levelling process of DC03 and DC04 steel sheets on their quality in terms of further application for products formed in technologies used in the automotive industry. The straightening process was carried out in a demonstration line developed as part of a project carried out by DAR STAL Dariusz Zaława together with the Łukasiewicz Research Network – Institute for Ferrous Metallurgy. The study examined the influence of stretch levelling on waviness and the state of internal stresses of the sheets. It was found that the use of stretch levelling with a controlled elongation value results in obtaining a favourable and stable state of stress in the sheets. No significant influence of the straightening process on the structure and mechanical properties of the sheets was found.

Keywords: *steel sheet, stretch levelling, residual stresses, sheet flatness, structure*

W ramach artykułu opisano wpływ procesu prostowania naciągowego blach ze stali DC03 i DC04 na ich jakość pod kątem dalszego przeznaczenia na wyroby kształtowane w technologiach stosowanych w przemyśle motoryzacyjnym. Proces prostowania prowadzono w linii demonstracyjnej opracowanej w ramach projektu realizowanego przez firmę DAR STAL Dariusz Zaława wspólnie z Sieć Badawcza Łukasiewicz – Instytutem Metalurgii Żelaza. W ramach pracy badano wpływ prostowania naciągowego na falistość i stan naprężeń własnych blach. Stwierdzono, że zastosowanie prostowania naciągowego, z kontrolowaną wartością wydłużenia, powoduje uzyskanie korzystnego i stabilnego stanu naprężenia w blachach. Nie stwierdzono znaczącego wpływu procesu prostowania na strukturę oraz właściwości mechaniczne blach.

Słowa kluczowe: *blacha stalowa, prostowanie naciągowe, naprężenia własne, płaskość blach, struktura*

1. INTRODUCTION

The requirements of the recipients of semi-finished products and steel products focus not only on the mechanical properties and shape defects, but more and more often they relate to the internal state of stress [1, 2]. This is a particularly important issue for the automotive industry, where steel sheets are cold-formed exactly to the dimensions of car body parts. After hot rolling, residual stresses are generated in the sheets as a result of inhomogeneous plastic deformation, uneven cooling and phase transitions [3, 4]. From the point of view of the physics of the phenomenon, internal stresses can be compared to the potential energy stored in the material, including the potential for stress relaxation in the processing of a semi-finished product into a final product. The stress state developed in the hot rolling process changes significantly during cold rolling. It is very important that this condition does not adversely affect the processes of further processing of the sheets into the final product and the behaviour of the component under operating conditions. In the process of processing metal sheets, a particularly trouble-

some phenomenon – caused by stress relaxation – is the change of shape during thermal cutting, which may, for example, damage the cutting head, leading to damage to the cut component. In the event that any section of the sheet is subjected to cold rolling, it is very important to use such roller settings that the original shape of the sheet is reproducible for each coil. Due to the inhomogeneous distribution of plastic strain in the cold rolling process, the residual stresses occur in the sheets after rolling. When the strain distribution is symmetrical with respect to the neutral plane of the sheet, it should not show waviness/flatness deviation. Deviations from this rule may result from an uneven residual stress distribution caused by one or more of the following factors:

a) difference in the diameters between the upper and lower rollers,
b) differences in the rotational speed of the working rollers,
c) differentiation of friction conditions along two planes of contact with the rollers,
d) no perpendicularity between the plane with the rollers and the sheet's plane,
e) deviation of the sheet from its symmetrical pass-through line at entry and/or exit from the rollers.

The occurrence of one or more of these factors causes heterogeneity of the plastic deformation in the cross-section of the sheet. The differentiation of the plastic flow conditions on the cross-section of the sheet, and as a result – of the internal stress, is of particular importance in the process of cutting forms or blanks from sheets for use in the automotive or household appliances industry, where the unfavourable distribution of stresses most often leads to their relaxation after cutting and, as a result, causes undesirable changes in the shape of the product. Deviations from flatness are crucial from the point of view of the production of sheets for semi-finished products for the automotive industry, such as: body parts, mounting components for various types of covers, electrical and electronic components. For this reason, the sheets should have the required dimensional tolerance and the minimum level of residual stress, as well as their favourable distribution along the length and cross-section of the sheet. For this purpose, after cold rolling, straightening is performed, consisting in bending between the rolls with the use of a roller straightener, and in necessary cases also plastic stretching of the sheets with a stretch leveller. As a result of the straightening, the desired flatness of the sheets is obtained, and the level of residual stresses is also reduced.

The aim of the study carried out in the project by DAR STAL Dariusz Zaława together with the Łukasiewicz Research Network – Institute for Ferrous Metallurgy was to develop an innovative process for the production of sheets for use in the automotive industry, ensuring at the same time the required flatness of the semi-finished product and favourable distribution of internal stresses, allowing for the correct course of the production process of the final product. An important element of the new process is the control of the state of internal stresses in industrial conditions, as the lack of such control may result in the occurrence of unfavourable stress states in the sheets, even if the dimensional tolerance and shape requirements of this semi-finished product are met.

2. CONTROL AND MONITORING OF STRESS STATE IN THE PRODUCTION PROCESS

The issue of residual stress control in technological processes, in particular in sheet metal straightening operations, has been the subject of intensive research conducted mainly in foreign centres [5–7]. It is a very complex issue covering both monitoring and analysis of the production process, as well as quality control. The analysis of the production process is very often based on the results of numerical simulations, as it allows to identify the causes of stress generation in the production process [4]. Countermeasures can also be taken based on numerical simulations, but first it should be considered if corrective actions are required as internal stresses are not always the cause of operational problems. For example, compressive stresses increase resistance to fatigue. It should be emphasised that the possibilities of changes in the technological process aimed at reducing the level of residual stresses are limited. Then, consideration should be given to the application of additional stress relaxation measures, including plastic working and heat treatment [8].

The sheet metal manufacturing technology at DAR STAL Dariusz Zaława was based on the use of additional plastic deformation after cold rolling with the use of a stretch leveller. In the straightener, the sheet after cold rolling is gripped by jaws and then elongated by a given deformation value. It was assumed that the value of the applied deformation should depend on the value of yield strength and consists of two components, one corresponding to the deformation to the yield strength and the other ensuring the generation of an appropriate number of slip systems, causing stress relaxation. The value of the first component is calculated knowing the value of yield strength and the spring constant (R_e/K). In the case where the steel exhibits the Lüders effect, the value of the additional deformation was 10–20% of Lüders deformation. On the other hand, for steels characterised by the occurrence of apparent yield strength, the value of the additional deformation was calculated assuming that it should cause additional hardening of the material by 10–20 MPa.

Another issue related to the implementation of the project was the selection of the method of stress measurement. The characteristics of the applied methods of stress measurement are presented in

[8, 9]. Due to the conditions of the project, a measurement method based on X-ray diffraction was selected for this purpose, which is classified as a non-destructive method, and its advantage is that it is a direct method that allows to measure the components of the crystal lattice deformation and directly convert them into stress components. In addition, the measurement is based on the $\cos(\alpha)$ method which allows the detection of the entire Debye-Scherrer ring, which increases the accuracy and shortens the measurement time compared to the traditionally used $\sin^2(\psi)$ method [10]. In industrial conditions, measurements were carried out using the magnetic method with the Barkhausen effect. However, this method requires calibration of the device in order to obtain results in MPa.

The further part of the paper presents the results of the research confirming the adopted concept of the production process, as a result of which the developed technology was implemented at DAR STAL Dariusz Zaława.

Fig. 1. Demonstration line with stretch leveller

Rys. 1. Widok linii demonstracyjnej z prostownicą naciągową

3. MATERIAL AND TESTING METHODOLOGY

The material for the tests consisted of sections taken from DC03 and DC04 steel sheets after cold rolling and final heat treatment before and after stretch levelling performed with the use of the demonstration installation developed and built within project [11]. The line is shown in Fig. 1. The basic components of the demonstration installation are the stretch levelling line and the cross-cutting line. The decoiler feeds the sheet to a tensioning device with four 800 mm diameter rollers, and then to a cassette stretch leveller with non-driven rollers in a six-roller arrangement. After the stretch leveller, a second system of stretching rollers is installed, also with a diameter of 800 mm. The stretch levelling line allows the sheet to be elongated up to 3% of its original length, which guarantees reaching and exceeding yield strength, and as a result, relaxation of the material's residual stresses and removal of flatness defects. Behind the stretch leveller there is a line for cutting sheets into pieces, and the last component of the line is a laser cutter with which the sheets are inspected after stretch levelling.

The dimensions and characteristics of the sheets from which the test samples were taken are shown in Table 1, and their chemical composition is shown in Table 2.

Table 1. Characteristics of the DC03 and DC04 steel sheet manufacturing process

Tabela 1. Charakterystyka procesu wytwarzania arkuszy blach ze stali DC03 i DC04

Steel grade	Cold rolling with the use of a four-roller reverse rolling mill and coil heat treatment in a bell-type furnace	Final size of sheets [mm]
DC03	• Rolling in 3 passes from a thickness of 1.84 mm to 1.52 mm • Annealing at 690°C for 330 min., cooling under a hood with forced air • Rolling in 1 pass from a thickness of 1.52 mm to 1.50 mm • Cutting to the final width of 330 mm in the longitudinal cutting line • Stretch levelling with a sheet elongation of 0.4% and cross-cutting into 990 mm long forms	1.50 × 330 × 990
DC04	• Rolling in 5 passes from a thickness of 1.95 mm to 0.62 mm • Annealing at 700°C for 330 min., cooling under a hood with forced air • Rolling in 1 pass from a thickness of 0.62 mm to 0.60 mm • Cutting to the final width of 380 mm in the longitudinal cutting line • Stretch levelling with a sheet elongation of 0.2% and cross-cutting into 760 mm long forms	0.60 × 380 × 760

Table 2. Chemical composition of the tested sheets, [wt%]

Tabela 2. Skład chemiczny badanych blach [% mas.]

Steel grade	[wt%]												
	C	Si	Mn	P	S	Cr	Ni	Cu	Mo	Ti	Al	V	B
DC03	0.088	0.026	0.412	0.014	0.007	0.029	0.017	0.004	0.025	<0.026	0.042	0.016	<0.0009
DC04	0.075	0.014	0.323	0.015	0.003	0.060	0.049	0.006	0.034	<0.004	0.056	<0.015	<0.0003

Before and after stretch levelling, the sheets were measured for flatness, mechanical properties, and structure, and residual stresses were analysed.

In order to assess the flatness, a method based on the measurement of the curvature of the sheets was used and the values of the I index were determined, in accordance with formula (1) [11]:

$$\text{Flatness in } I \text{ unit} = \left(\frac{\pi H}{2L}\right)^2 \cdot 10^5 \qquad (1)$$

where:

H – wave height,
L – wave length.

After transformation, relation (1) takes form (2):

$$\text{Flatness in } I \text{ unit} = 24{,}7S^2 \cdot 10^4 \qquad (2)$$

where:

$S = H/L$

The static tensile tests were carried out using a Zwick/Roell Z250 universal testing machine. According to the PN-EN ISO 6892-1 standard, for sheets with a thickness of ≤3 mm, the tests were carried out on non-proportional samples with a measuring length of 80 mm.

The following were determined as a result of the conducted static tensile tests:

– yield strength ($R_{p0.2}$)
– tensile strength (R_m)
– percent elongation after fracture (A_{80mm}).

The structure was examined using an OLYMPUS DSX 500i optical-digital microscope.

The measurement of the sheets' residual stresses was performed with the use of a Pulstec µ-X360s portable X-ray stress analyser. The analyser is equipped with a highly sensitive flat detector, allowing the stresses to be determined in a single measurement. The working conditions of the X-ray tube were 30 kV and 1 mA. A lamp with a chrome anode was used. A collimator with a 2 mm diameter was used. The depth of penetration of X-rays is approximately 10 microns. The measurement was taken in the same locations on both surfaces of the sheets before and after straightening. Then, the average values of the distribution of residual stresses on both sides of the sheet in the direction of rolling and the difference between the average values on both sides were determined.

4. STUDY RESULTS

The results of the flatness tests of sheets before and after stretch levelling are presented in Table 3. Sheets made of DC03 and DC04 steel in the condition after longitudinal cutting and before straightening were characterised by central and side corrugation, respectively. As a result of stretch levelling, a significant reduction in the value of sheet waviness was obtained.

The results of the examination of the mechanical properties of sheet samples are presented in Table 4. The obtained mechanical properties of the sheets correspond to the values specified in the standard for DC03 and DC04 steel sheets. The stretch levelling process does not significantly change the mechanical properties of the sheets.

The tested steel sheets are characterised by a ferritic structure, typical of a recrystallised material (Figs. 2 and 3). There was no differentiation of the

**Table 3. Characteristics of sheet waviness**
Tabela 3. Charakterystyka falistości blach

| Sheet state	Characteristics	Waviness expressed in I unit
DC03 after longitudinal cutting	corrugation in the central area about 9 mm high over a distance of 952 mm	I = 22.07
DC03 after 0.4% stretch levelling and cross-cutting	central corrugation about 2 mm high over a distance of 621 mm	I = 2.56
DC04 after longitudinal cutting	lateral corrugation about 5 mm high over a distance of 637 mm	I = 15.21
DC04 after 0.2% stretch levelling and cross-cutting	lateral corrugation 1 mm high over a distance of 685 mm	I = 0.53

Table 4. Results of examination of mechanical properties
Tabela 4. Wyniki badań właściwości mechanicznych

Item	Sample identification	Yield strength $R_{p0.2}$ [MPa]	Tensile strength R_m [MPa]	Elongation A_{80mm} [%]
1	DC03 after longitudinal cutting	200	315	39.4
2	DC03 after 0.4% elongation	202	324	40.6
3	DC04 after longitudinal cutting	197	285	38.4
4	DC04 after 0.2% straightening	188	280	40.6
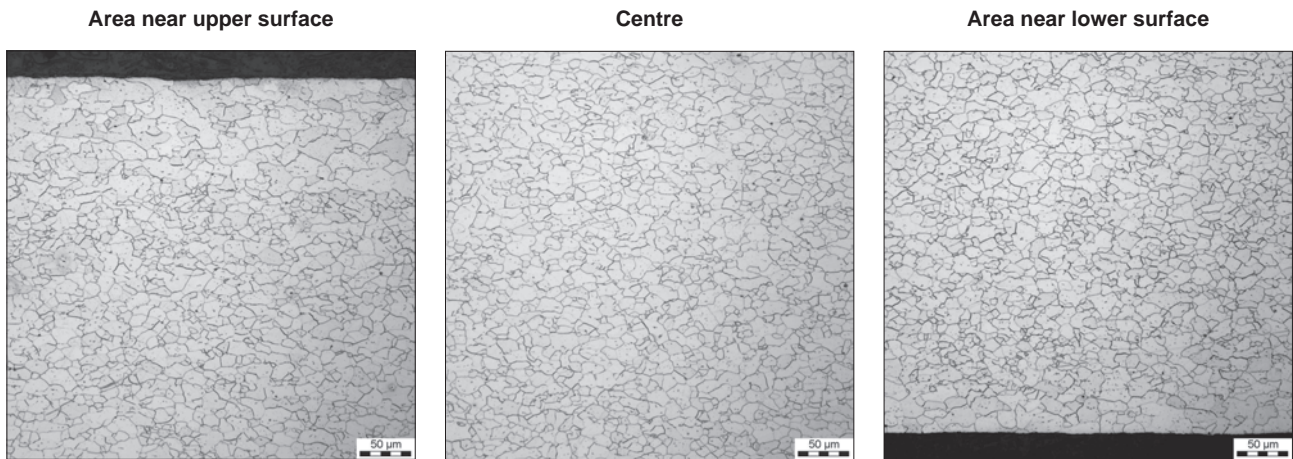
Area near upper surface	Centre	Area near lower surface

a) sheet after longitudinal cutting, before stretch levelling
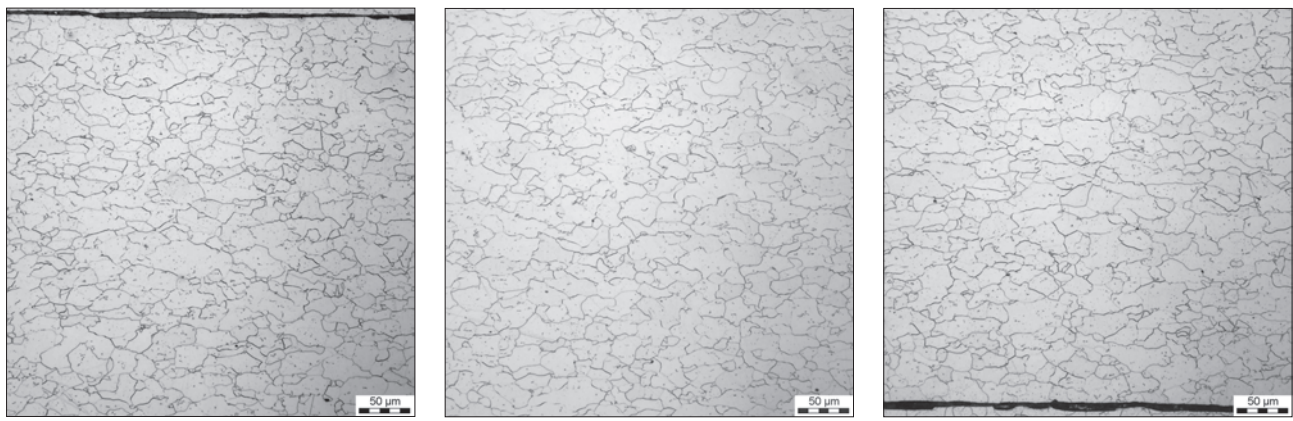
b) sheet after stretch levelling

Fig. 2. Structure of DC03 steel sheet: a) before stretch levelling, b) after stretch levelling with 0.4% elongation

Rys. 2. Struktura blachy ze stali DC03: a) przed prostowaniem naciągowym, b) po prostowaniu naciągowym

structure between the subsurface areas and the centre of the sheet thickness. The process of stretch levelling of DC03 and DC04 steel sheets with the applied tension values of 0.4% and 0.2% does not cause changes in their structure visible under a light microscope both in the subsurface and in the central areas (Figs. 2 and 3).

As already mentioned, a very important issue for sheets intended for the automotive industry is the distribution of residual stresses, which determines the behaviour of the material during further shaping. The distribution of residual stresses in the tested sheets was determined for sections of 100×500 mm sheets with before and after stretch levelling. 20×40 mm measurement fields were marked on the sheet sections, as shown in Figure 4. Corresponding points on both sides of the sheets are marked with the same colour.

The results of the residual stress distribution on both sides of the surface of the tested sections are shown in Figures 5–8. In the tested sheets, tensile stresses and compressive stresses occur on both sides (Figs. 5–8).

From the point of view of the behaviour of the sheets during their further shaping, a very important issue is the difference in internal stresses (in the direction of rolling) occurring on the opposite sides of the sheets. Hence, average values of residual stresses were determined for the upper and lower surfaces of the sheets. Then, the difference in residual stresses between the upper and lower surfaces of the sheets was calculated from the average values. The values of the differences in the average values of residual stresses of the tested samples before and after stretch levelling, together with the absolute values of the differences in stress values, are presented in Table 5.

The applied stretch levelling of DC03 and DC04 steel sheets with an elongation of 0.4% and 0.2%, respectively, led to a reduction in the difference in stress values between both surfaces of the tested sheets in the rolling direction. Average differences in the sheets' residual stresses between the upper and lower surface of the sheets after straightening do not exceed 15 MPa. Based on the experience of the authors of this study, it appears that such values do not deform the sheet after cutting.

Area near upper surface	Centre	Area near lower surface

a) sheet after longitudinal cutting, before stretch levelling
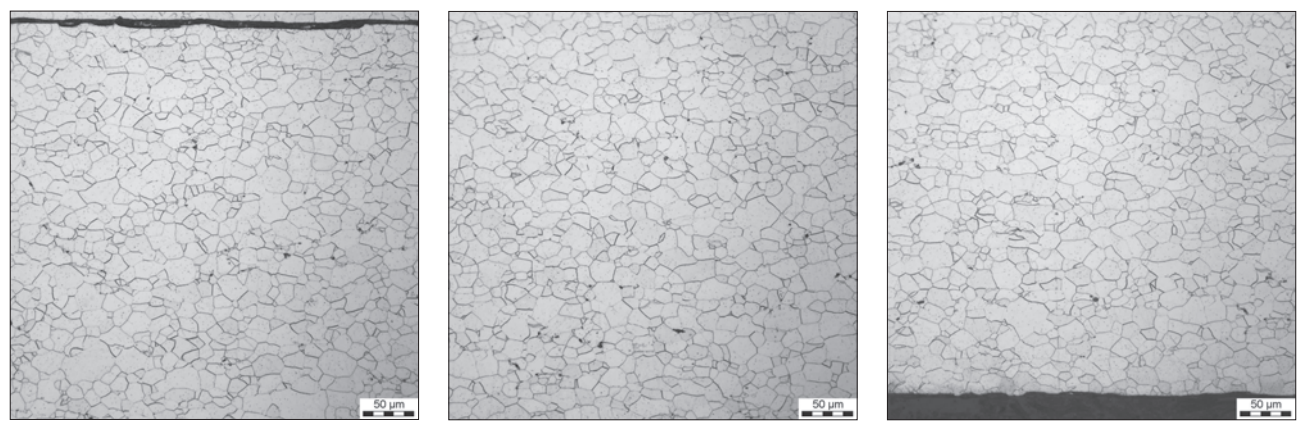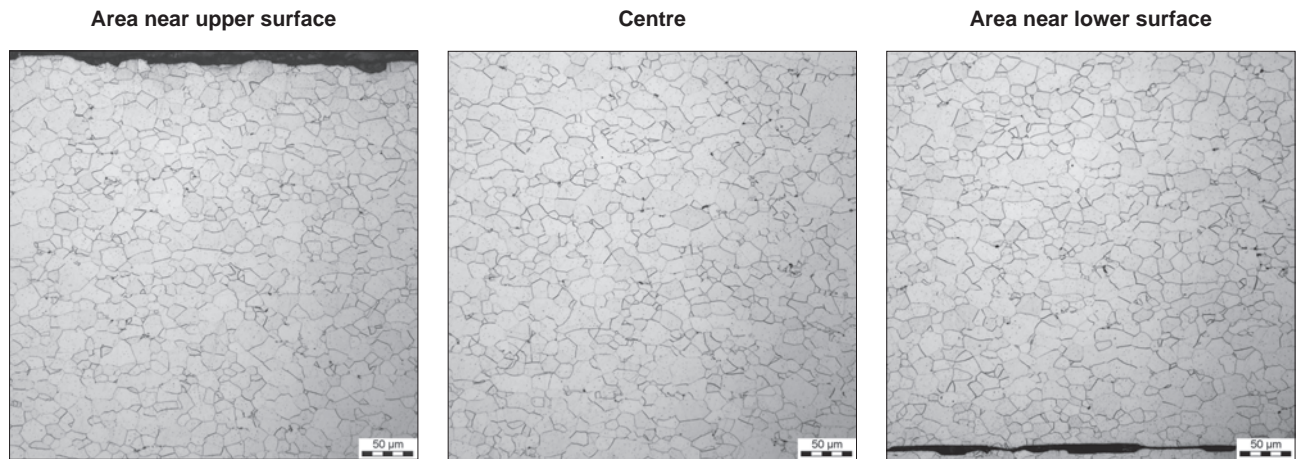

b) sheet after stretch levelling

Fig. 3. Structure of DC04 steel sheet: a) before stretch levelling, b) after stretch levelling with 0.2% elongation

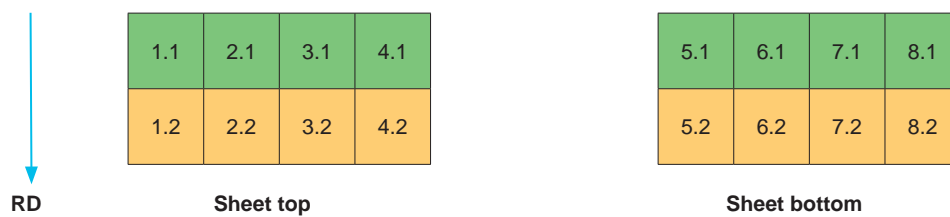Rys. 3. Struktura blachy ze stali DC04: a) przed prostowaniem naciągowym, b) po prostowaniu naciągowym

Fig. 4. Identification of stress measurement locations; RD – rolling direction

Rys. 4. Siatki pomiarowe, dla których wykonano pomiary naprężeń; RD – kierunek walcowania (KW)

Fig. 5. Residual stress distribution of the upper (a) and lower (b) surface of the DC03 steel sheet before stretch levelling; RD – rolling direction

Rys. 5. Rozkład naprężeń własnych górnej (a) oraz dolnej (b) powierzchni blachy ze stali DC03 przed prostowaniem naciągowym; RD – kierunek walcowania (KW)
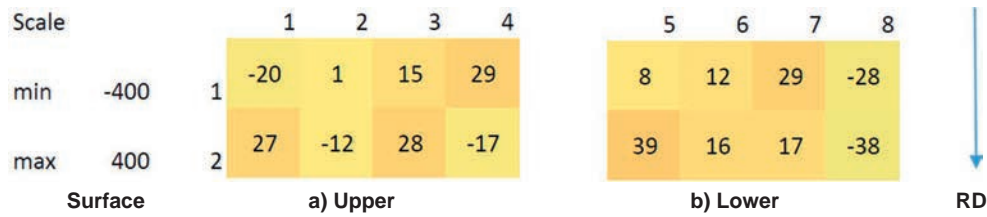
Fig. 6. Residual stress distribution of the upper (a) and lower (b) surface of the DC03 steel sheet after stretch levelling; RD – rolling direction

Rys. 6. Rozkład naprężeń własnych górnej (a) oraz dolnej (b) powierzchni blachy ze stali DC03 po prostowaniu naciągowym; RD – kierunek walcowania (KW)
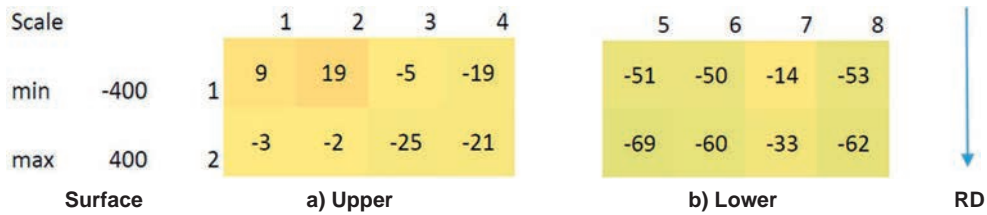

Fig. 7. Residual stress distribution of the upper (a) and lower (b) surface of the DC04 steel sheet before stretch levelling; RD – rolling direction

Rys. 7. Rozkład naprężeń własnych górnej (a) oraz dolnej (b) powierzchni blachy ze stali DC04 przed prostowaniem naciągowym; RD – kierunek walcowania (KW)
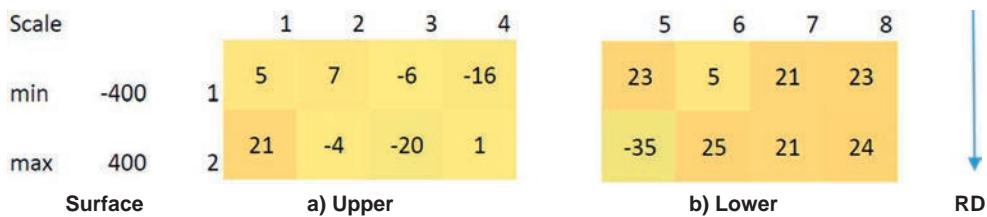

Fig. 8. Residual stress distribution of the upper (a) and lower (b) surface of the DC04 steel sheet after stretch levelling; RD – rolling direction

Rys. 8. Rozkład naprężeń własnych górnej (a) oraz dolnej (b) powierzchni blachy ze stali DC04 po prostowaniu naciągowym; RD – kierunek walcowania (KW)

Table 5. Difference in the values of residual stresses between the upper and lower surfaces of the sheets

Tabela 5. Różnica wartości naprężeń własnych pomiędzy górną i dolną powierzchnią blach

Sample identification	Average stress value [MPa]		Absolute value from difference of stress values [MPa]
	sheet's upper surface	sheet's lower surface	
DC03 before stretch levelling	-22.0	-13.4	8.6
DC03 after stretch levelling	6.4	6.9	0.5
DC04 before stretch levelling	-5.9	-49.0	43.1
DC04 after stretch levelling	-1.5	13.4	14.9

6. DISCUSSION

The basis for the implementation of the project was the hypothesis that the use of stretch levelling after cold rolling of DC03 and DC4 grade sheets will not only allow to obtain the required flatness, but also lead to a reduction in the stress level in the sheets, and with a properly selected elongation value, the absolute difference of the average stress value determined on both surfaces of the sheet will be negligi-ble. Moreover, it was found that for each steel grade it is possible to define a threshold value of this difference for the correct course of the cutting process, without bending of the cut component. In the case of the tested steels, the cutting process is correct when the difference is lower than approximately 30 MPa. Moreover, it has been found that in order to obtain a favourable stress distribution after stretch levelling, the value of the applied elongation should slightly exceed the value of the strain to yield strength in the

static tensile test. The research has shown that the application of the stretching method does not cause drastic changes in the structure in the micro scale, as well as in the mechanical properties. This is due to the fact that the dislocation density after slight plastic deformation is not high enough to cause significant changes in structure and properties.

5. CONCLUSIONS

Based on the tests of DC03 and DC04 steel sheets before and after stretch levelling performed in the demonstration line, it can be concluded that:

1. Stretch levelling with the applied tension values resulted in a reduction of sheet waviness expressed in I units by 88% in the case of the DC03 steel sheet and by 96% for the DC04 steel sheet.
2. The stretch levelling process does not significantly change the mechanical properties of the sheets.
3. The sheets have a ferritic structure characteristic of a recrystallised material. There was no significant influence of the straightening process of the sheets on their structure in the subsurface areas and in the centre of the sheets' thickness.
4. Stretch levelling significantly reduces the differentiation of residual stresses in the sheets. The values of residual stresses after straightening do not exceed the value of 40 MPa, while their difference, expressed in absolute value, between the upper and lower surfaces of the tested sheets after straightening does not exceed 15 MPa. The obtained stress values ensure no deformation of the material in subsequent processes of shaping the material for finished products.

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