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# VARIATIONS OF THE RHEOLOGICAL PROPERTIES OF STEEL IN THE PLATE ROLLING PROCESS CONDITIONS

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ABSTRACT

The article presents the results of investigation into of the rheological properties of steel S355J2+N, while considering the influence of deformation, temperature and strain rate. Tests were carried out using a metallurgical process simulator Gleeble 3800. Based on the plastometric tests, stress–strain diagrams for the steel were developed and the coefficients of the flow stress function were selected. The obtained rheological testing results were used in computer simulations of the asymmetric plate rolling in the 3600 Plate Rolling Mill.

## Introduction

Rolling flat products is among the most common and most frequently applied plastic working processes used to form metals. The manufacture of flat products and implementing them in various fields of industry, such as the defence, automotive, household articles, conventional, wind and nuclear energy industries is the hallmark of the scale of modernity and development of a given country's metallurgical industry.

Flat products must meet the requirements of demanding purchasers in terms of their plastic properties, shape and allowable thickness deviations, or chemical compositions.

Among flat products, plates and slabs make up an important group. They are most commonly manufactured in tandem plate rolling mills equipped with a vertical roll stand and 2 horizontal four-high stands, on which rolling is done by the reversing method.

When the stock is fed to the roughing stand, and the band is fed to the finishing stand of the Plate Rolling Mill, the neutral axis of the stock or band is, in the majority of cases, does not coincide with the neutral axis of the roll gap; whereas, the shorter the band, the larger the angle at which it is introduced to the deformation zone. As a consequence, the geometrical conditions of band deformation on the upper and lower working roll sides are disturbed, and the rolling process itself becomes an asymmetric process, which will vary in each subsequent pass [1, 2]. This phenomenon causes an adverse bending of the band towards either lower or upper roll. The bent band is then straightened by roller table rollers; yet, its beginning has a permanently distorted (wavy) shape. So distorted product is difficult to "repair", or straighten, either in a further rolling process, or on separate straightening machines, due to the high rigidity of the band.

Based on many years' studies and analysis of the quality of products manufactured in the Plate Rolling Mill, we can state that a large technological waste occurs during this production, which is due to the waviness of the rolled bad front end. Moreover, the rolling mill equipment and roller table rollers undergo rapid wear.

In order to prevent the phenomenon of band front end bending after band exit from the roll gap, a modern work table level setting system should be implemented, which would enable the so-called neutral line of the rolled feedstock to coincide with the neutral line of the roll gap in each successive rolling pass. Another alternative method of improving the band shape is to introduce a controlled asymmetric rolling process, which will rely on the use of differentiated rotational speeds of individual working rolls [3–5]. By introducing such an asymmetry (i.e. kinetic asymmetry), the state of stress and strain in metal in the roll gap could be changed, thus eliminating the adverse bending of the front end of band exiting the deformation zone [6].

It should be remembered, however, that apart from its advantages, the asymmetric process has also some drawbacks. These include the possibility of overloading the rolling mill drives and the occurrence of slips in the roll bite. Therefore, in order to eliminate those drawbacks prior to implementing the asymmetric rolling process in industrial conditions, theoretical research on this process should be carried out beforehand. A theoretical analysis of the process of rolling plates of steel S355J2+N on the roughing mill of the 3600 Plate Rolling mill taken as an example was made using FORGE 2018, a software program based on the finite element method.

A basis for the correct simulation and design of technological processes is a good knowledge of characteristics describing the engineering properties of the material. For each technological process, a set of features that well describe the suitability of the material for a given process can be determined. For plastic working processes, a key feature characterizing the susceptibility of material to plastic deformation is the flow stress $\sigma_p$.

The flow stress $\sigma_p$ is defined as a stress value necessary for initiating and continuing the plastic flow of metal under the conditions of the uniaxial stress state occurring simple tension or compression. Its value depends on the deformation conditions, mainly on the specimen temperature ($T$), the value of true strain ($\varepsilon$), the mode of this strain increasing in time $\varepsilon(t)$, and on the strain rate ($\dot{\varepsilon}$) [7].

## Purpose of the study

The purpose of the study was to determine the rheological properties of steel S355J2+N and to present the testing results in the form of stress–strain diagrams, while considering the effect of rolled band temperature and strain rate. Based on the tests, diagrams of the stress–strain relationship for the steel were determined and the coefficients of the flow stress function were selected, which were used in subsequent computer simulations of the rolling process. The diagrams of strains, strain rates and variations in specimen temperature during testing the plastic properties of the steel were determined based on data obtained from the actual rolling process conducted in a selected Plate Rolling Mill.

## Examination of the rheological properties of steel

The determination of the engineering plasticity characteristics is especially difficult for hot plastic working conditions, because the considerable plastic deformation preset for this kind of working is accompanied by significant strain hardening. In such conditions, recovery and dynamic recrystallization processes proceed intensively in the metal [7–11]. The rheological behaviour of deformed materials is sufficiently adequately characterized by flow curves, $\sigma_p$–$\varepsilon$, whose progresses result from interactions between strain hardening processes, recovery processes and dynamic and meta-dynamic recrystallization processes. By knowing these processes and controlling them, it is possible both to optimize the energy–force and engineering parameters of various metal plastic working processes, as well as to significantly influence the physical and mechanical properties and the structure of finished products.

The correct determination of the steel properties in the form of stress–strain diagrams, allowing for the effect of band temperature and strain rate for the actual plastic working process, makes it possible to enhance the accuracy of calculations when using empirical formulas, as well as numerical computations using the finite element method [12–14]. Within the study, plastometric tests were carried out on steel S355J2+N, based on which the steel property diagrams were developed and the coefficients of the flow stress function were selected, which were used when conducting computer simulations of the asymmetric rolling process.

The flow stress, as dependent on the rolling process parameters, was determined from hot compression tests. The tests were carried out using the Gleeble 3800 metallurgical process simulator (**Fig. 1**), at the Institute for the Modelling and Automation of the Czestochowa University of Technology.

This device enables tests to be carried out at temperatures corresponding to the actual rolling process conditions. The tests were carried out in a vacuum chamber at a constant specimen deformation temperature. For the plastometric tests, flat 10x15x20 mm specimens were used. To limit the non-uniform specimen deformation ('barelling') caused by friction, tantalum or graphite washers and special graphite-based grease were put between the specimen face surfaces and the tool surfaces. For the recording and control of temperature, two $K$-type thermocouples installed on the specimen lateral surface were used. The cylindrical specimens were heated by a resistance method using anvils. To minimize the influence of scale on the quantity being determined, the tests were performed in vacuum. General view of the test specimen and the device's chamber is shown in **Fig. 2**.

Based on the plastometric tests, stress–strain relationship diagrams were developed for steel S355J2+N (**Fig. 3**) and the coefficients of the flow stress function were selected (1), which were used in computer simula-

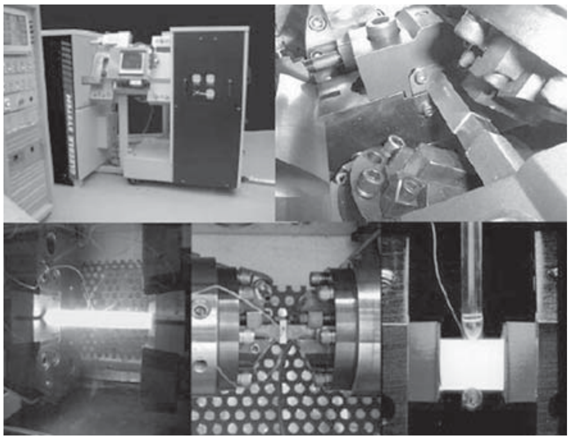

**Fig. 1. The Gleeble 3800 physical simulator**

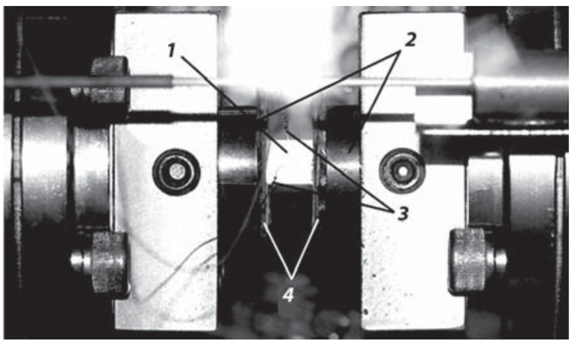


**Fig. 2. A specimen during testing in the device's chamber:** *1* — specimen; *2* — anvils; *3* — $K$-type thermocouples; *4* – layers of tantalum or graphite washers separated by graphite-based grease

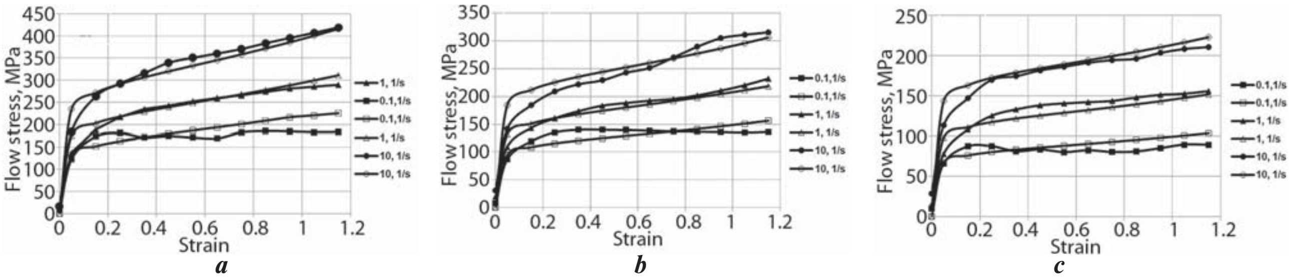


**Fig. 3. The work-hardening curves for steel S355J2+N for the strain rate range of (0.1 s$^{-1}$ – 10 s$^{1}$):**
*a* — at 800 °C; *b* — at 900 °C; *c* — at 1000 °C; solid symbols — experimental curves; hollow symbols — approximated curves

tions of the rolling process. The values of the equation coefficients are given in **Table 1**. Chemical composition of the steel is given in **Table 2**.

$$\sigma_P = Ae^{m_1T} e^{m_2} \dot{\varepsilon}^{m_3} \varepsilon^{\frac{m_4}{\varepsilon}} (1+\varepsilon)^{m_5T} \varepsilon^{m_7\varepsilon} \dot{\varepsilon}^{m_8T} T^{m_9}. \quad (1)$$

If follows from the data in **Fig. 3, *a, b, c*** that during the deformation of the steel under study at a low strain rate of $\dot{\varepsilon} = 0.1$ and with small values of true strain, steel strain hardening can be observed in the entire examined temperature range of 800÷1000 °C — which manifests itself in an increase in the value of flow stress.

After exceeding the limiting strain, dynamic recrystallization occurs to a small extent, and the recovery effects are caused rather by dynamic recovery, which is shown in the strain hardening curves by the appearance of a constant value of $\sigma_p$ with the increase in true strain. For higher strain rates of $\dot{\varepsilon} = 1.0$ and 10.0 s$^{-1}$, for the entire examined temperature interval, the steel shows strain hardening, and the recovery processes occur too slowly to remove the cold work effects. A distinct increase in flow stress magnitude is observed.

The testing results obtained from the performed plastometric tests were used in computer simulations of the asymmetric rolling process.

## Verification of the parameters of the asymmetric plate rolling process in the laboratory rolling mill

To verify the theoretical examination results obtained using the FORGE software program, a series of experimental tests was carried out on a D300 laboratory two-high mill. The experimental test programme was prepared using the geometric similarity law for strip shape factors of $h_0/D = 0.14$–0.0660. For physical modelling — experimental modelling, the same steel grade as in the theoretical examination was used.

## Description of the testing stand

A D300 rolling mill with a working roll diameter of 300 mm and roll face length of 300 mm. The roll surfaces were in an as-ground condition. The maximum rolling force of the rolling mill is 500 kN, while the permissible rolling torque on a single roll is 20 kNm.

Each roll of the 300 two-high mill has an individual drive from a 75 kW rated power asynchronous AC motor via a 1:40 transmission ratio reduction gear and a drive shaft. The motor is controlled by an ASC800-type frequency converter supplied by ABB Industry. The converter enables the motor's rotational speed and rotation direction to be freely controlled within the range of 0÷1000 rpm and, in addition, it allows the continuous monitoring of variations in rolling speed and rolling torque. The nominal rolling speed at the rotational speed of 1000 rpm is 0.45 m/s. Setting up the roll gap in the range from 0 to 70 mm is done automatically with adjustment screws activated by electric motors. The measurement of the pressure force is made using two CL-21 extensometric sensors, each with a measuring range of 250 kN. The sensors are arranged between the upper roll bearing housings and the adjustment screws. Sensor signals, after being amplified in CL100P in industrial extensometric amplifiers, were recorded by a PLC controller which records also the values of motor shaft torques. During the rolling process, the current pressure force and rolling toque values are shown both graphically and numerically in the controller's display.

The strip is fed to and received from the rolling stand, respectively, with one of the two 3 m-long working roller table sections located on the either side of the stand. The

Table 1. **The values of the parameters *A* and $m_1 \div m_9$ used for determining the values of $\sigma_p$ for steel S355J2+N**

| Steel | The values of theм parameters *A* and $m_1 \div m_9$ used for determining the values of $\sigma_p$ | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | *A* | $m_1$ | $m_2$ | $m_3$ | $m_4$ | $m_5$ | $m_7$ | $m_8$ | $m_9$ |
| S355J2+N | 0.000155 | –0.005730 | 0.389854 | –0.084144 | –0.000175 | –0.001172 | –0.229122 | 0.000221 | 2.950474 |

Table 2. **Chemical composition of the steel used for the tests, %**

| Steel | C | Mn | Si | $P_{max}$ | $S_{max}$ | Cr | Ni | Cu | Mo | Nb | Ti | Al | N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S355J2+N | 0.15 | 1.365 | 0.33 | 0.017 | 0.03 | 0.05 | 0.089 | 0.23 | 0.03 | 0.002 | 0.002 | 0.03 | 0.0092 |

roller tables have a reverse working capability with variable speed regulation. They also enable the adjustment of the work table level height to allow the strip to be fed into the rolls at an angle.

The rolled feedstock temperature was measured using two OPTRIS PI 160 thermovision cameras with thermal shields and adjustable holders. Each of the cameras enabled the rolled strip temperature to be measured up to 1500 °C. Moreover, having the function of a linear scanner, the cameras make it possible to examine the profile of temperature distribution over the strip width with a resolution of up to 160 points. On account of the conditions prevailing during the rolling of the strip and its cooling (high temperature and humidity), the cameras were positioned within thermal shields of protection rating IP67 which allowed the cameras to operate in the temperature range from ambient temperature to 240 °C with a both water and air cooling capability. Positioning the cameras at the rolling stand entrances enabled the strip temperature to be precisely determined prior and after rolling in each successive rolling pass. The thermovision cameras were fixed on booms mounted on the thermal shield supporting structure. The booms have the capability to adjust the position of the camera both horizontally and vertically, thanks to which the optimal field of vision of the camera can be set.

The image from the cameras was transmitted to a computer via the USB connector and then recorded and processed by a specialized software program supplied with the cameras. The software offers many advanced functions, such as the determination of the maximum and minimum temperatures in the area under examination, the determination of the average value and the recording of these values as a function of time.

**Laboratory testing programme**

For the examination of the force and energy parameters and the bend of the strip on exit from the deformation zone, specimens of steel S355J2+N were used. The specimen dimensions were chosen proportionally to the dimensions of the feedstock in the actual process of rolling in the roughing stand of the 3600 Rolling Mill. For the process of rolling in the D300 rolling mill, the feedstock was fed at an angle of 0°and 3° respectively. The specimens were rolled with a relative reduction of $\varepsilon = 0.2$. The asymmetry was introduced by differentiating the roll rotational speeds (the rotational speed of the upper roll was reduced by 10%).

The strip curvature radius was determined from this geometric formula:

$$r = (a^2 + 4f)/8f, \qquad (2)$$

where $f$ — deflection; $r$ — curvature radius; $a$ — chord length.

The deflection was determined in the following manner. The lateral specimen surface after rolling was mapped on graph paper, then the determined arcs were divided with chords and the deflection was measured from the centre of the chord.

The laboratory test results are shown in **Table 3**. The pressure force and temperature values provided in this table are mean values determined in accordance with the measurement methodology.

The data in Table 3 shows a good agreement between the numerical simulation results and the measurement results, both for the pressure force and the curvature of the strip after exit from the deformation zone. The error, as calculated in

Table 3. **Results of the verification of the parameters of the processes of symmetric and asymmetric rolling of S355J2+N steel plates with a reduction of e = 0.2 in the D300 laboratory rolling mill**

| Test No. | Dimensions, mm | Strip feed angle | Asymmetry factor $a_v$ | Pressure force, kN | | | Curvature, m$^{-1}$ | | | Forge temperature, °C | | Lab temperature, °C | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Forge | Lab. | Error | Forge | Lab. | Error | Entry | Exit | Entry | Exit |
| p09 | 20×160×450 | $\theta = 0°$ | $a_v$=1.00 | 380 | 390 | 0.026 | 0 | 0 | 0.000 | 1200 | 1180 | 1121 | 1147 |
| | | | | | 395 | 0.038 | | 0 | 0.000 | | | 1115 | 1135 |
| p10 | | $\theta = 3°$ | $a_v$=1.00 | 380 | 380 | 0.000 | 0.044 | 0.053 | 0.170 | 1200 | 1181 | 1146 | 1155 |
| | | | | | 385 | 0.013 | | 0.062 | 0.290 | | | 1150 | 1165 |
| p11 | | $\theta = 3°$ | $a_v$=1.10 | 400 | 375 | −0.067 | 1.211 | 1.356 | 0.107 | 1200 | 1185 | 1178 | 1165 |
| | | | | | 380 | −0.053 | | 1.421 | 0.148 | | | 1185 | 1200 |
| p12 | | $\theta = 0°$ | $a_v$=1.10 | 390 | 365 | −0.068 | 1.23 | 1.464 | 0.160 | 1200 | 1176 | 1163 | 1172 |
| | | | | | 370 | −0.054 | | 1.498 | 0.179 | | | 1170 | 1185 |
| p13 | 25×160×450 | $\theta = 0°$ | $a_v$=1.00 | 400 | 345 | −0.159 | 0 | 0 | 0.000 | 1220 | 1190 | 1169 | 1180 |
| | | | | | 350 | −0.143 | | 0 | 0.000 | | | 1180 | 1190 |
| p14 | | $\theta = 3°$ | $a_v$=1.00 | 390 | 440 | 0.114 | 0.042 | 0.052 | 0.192 | 1220 | 1192 | 1175 | 1180 |
| | | | | | 435 | 0.103 | | 0.037 | 0.135 | | | 1220 | 1225 |
| p15 | | $\theta = 3°$ | $a_v$=1.10 | 400 | 440 | 0.091 | 1.193 | 1.245 | 0.042 | 1220 | 1185 | 1210 | 1220 |
| | | | | | 445 | 0.101 | | 1.325 | 0.100 | | | 1200 | 1215 |
| p16 | | $\theta = 0°$ | $a_v$=1.10 | 400 | 410 | 0.024 | 1.196 | 1.534 | 0.220 | 1220 | 1191 | 1190 | 1205 |
| | | | | | 415 | 0.036 | | 1.423 | 0.160 | | | 1200 | 1219 |
| p17 | 42×160×450 | $\theta = 0°$ | $a_v$=1.00 | 480 | 495 | 0.030 | 0 | 0 | 0.000 | 1230 | 1203 | 1220 | 1235 |
| | | | | | 500 | 0.040 | | 0 | 0.000 | | | 1212 | 1220 |

Forge — computer simulation results; Lab. — results from the actual process of rolling in the laboratory rolling mill.

relation to the values obtained from computer simulations, for the pressure force ranged in most cases from 5 to 10%, while for the strip curvature, from 10 to 20%.

The discrepancies between the computer simulation results and the results obtained from the actual rolling process occurred due to the fact that the actual rolling process conditions differed from the ideal conditions existed during numerical simulations. In the real process, different friction conditions exist on the surface of contact between the metal and the working rolls. For the tests, new ground rolls were prepared, therefore the coefficient of friction on the metal–roll contact surface up to the moment of roll surface wear was lower than that adopted in the model. Moreover, the software program does not consider the layer of scale forming on the rolled specimen surface, which also influences the friction conditions.

In the real process, the distribution of temperature in the specimen volume is non-uniform, which is due to the design of the heating furnace, and specifically the furnace hearth, and the method of specimen supporting during heating.

The rolling end temperature value taken from the actual process, given in Table 3, is a reliable value, whereas the feedstock temperature might be burdened with an error resulting from the residues of scale left on the specimen surfaces, which formed during heating.

From the comparison of the theoretical examination results and their verification in the D300 two-high mill rolling process it can be argued that, when designing an asymmetric plate rolling process, one can rely on the results obtained from computer simulations carried out using the FORGE software program. The existing differences in pressure force and curvature radius values (the strip bend direction is forecast correctly) are acceptable and should not contribute to a disruption to the actual rolling process.

### Results of the asymmetric rolling process modelling studies

Working rolls, each of a diameter of 1103 mm, and a constant lower working roll rotational speed of $n$ = 55 rpm were assumed for the numerical studies of the rolling process. The range of applied relative reductions was $\varepsilon_w = 0.05–0.30$. The asymmetric rolling process was conducted by:

- changing the rotational speed of the upper roll to be lower than that of the lower roll (kinetic asymmetry). The range of variation of the roll rotational speed asymmetry factor, $a_v = v_d/v_g$, was 1.01–1.10.

- changing the angle of band feeding to the roll gap (geometric asymmetry). The range of variation of the feedstock feed angle was $\theta = 0 \div 3°$.

A band shape factor of $h_0/D = 0.1887$ and 0.0660, respectively, was assumed. The rolled feedstock temperature, $T$, for the steel under investigation was changed, depending on the initial height, $h_0$. Thus, when $h_0 = 200$ mm, the rolling temperature was $T = 950$ °C, while for $h_0 = 70$ mm, the rolling temperature was $T = 850$ °C.

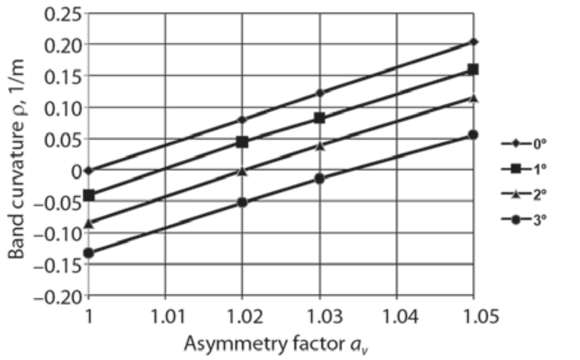


**Fig. 4. The effect of the asymmetry factor $a_v$ and the value of the deformation zone feedstock feed angle θ on the magnitude of band curvature after symmetric and asymmetric rolling 200 mm-high feedstock with a relative reduction of ε = 0.10**

### The effect of the relative reduction ε and the value of the roll gap band feed angle θ on the magnitude of band curvature ρ

Sample results of the investigation into the effect of the feedstock roll gap feed angle θ (geometric asymmetry) resulting from the non-coincidence of the feedstock neutral axis with the deformation zone neutral axis and the relative reduction ε on the band curvature magnitude, in symmetric and asymmetric rolling of feedstock of steel in grade S355J2+N are illustrated in **Fig. 4**.

The relationships illustrated in Figure 4 show that, in symmetric rolling, introducing the feedstock to the deformation zone at an angle of θ causes the front end of the exiting band to bend towards the lower roll. The band curvature grows with increasing feed angle. The application of the second type of asymmetry results in a change in band front-end bending direction. The data in this figure show that for each analyzed feedstock feed angle there is a kinetic asymmetry factor value, for which a straight band is obtained.

### Strain rate intensity fields and stress intensity fields

**Fig. 5 and 6** show sample distributions of strain rate intensities $\dot{\varepsilon}$the determined neutral surfaces on the upper roll side (in white) and on the lower roll side (in black) are also shown.

Feeding feedstock of an initial height of $h_0 = 200$ mm to the deformation zone at an angle of θ = 3° causes a non-uniform distribution of strain rates. In metal layers in contact with the upper roll, strain rate intensity values are greater than in layers in contact with the lower roll. The upper layers of the band metal move faster than the lower layers do, which results in the band front end bending towards the lower roll. As shown by the data in Fig. 5, the surfaces unaffected by the lower and the upper rolls (neutral surfaces) coincide with one another.

Introducing a small kinetic asymmetry ($a_v = 1.02$) to the rolling process produces a more uniform distribution of strain rate intensities, which results in a smaller band

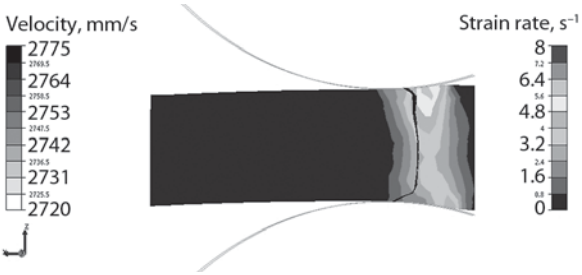


**Fig. 5. Distribution of strain rate intensities $\dot{\varepsilon}$ for feedstock of an initial height of $h_0$ = 200 mm, rolled with a reduction of ε = 0.10, with an asymmetry factor of $a_v$ = 1.00, and at a deformation zone feedstock feed angle of θ = 3°**

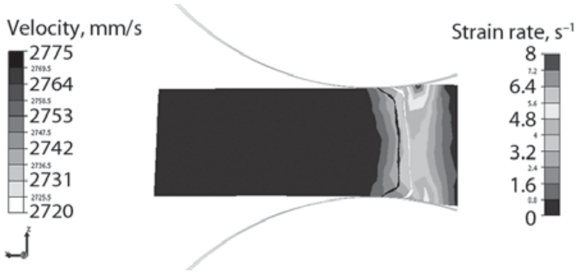


**Fig. 6. Distribution of strain rate intensities $\dot{\varepsilon}$ for feedstock of an initial height of $h_0$ = 200 mm, rolled with a reduction of ε = 0.10, with an asymmetry factor of $a_v$ = 1.02, and at a deformation zone feedstock feed angle of θ = 3°**

front-end bend. For this case, a slight bend towards the lower roll was obtained. It can be seen from the position of the neutral surfaces in the deformation zone that the advance zone on the upper roll side is longer than the lower roll affected advance zone, which contributes to the band bending towards the lower roll.

The results of the asymmetric rolling process tests were verified in laboratory conditions using a two-high rolling mill with a nominal working roll diameter of 300 mm and a roll face length of 300 mm, and a two-high rolling mill with a nominal working roll diameter of 150 mm and a roll face length of 200 mm. A good agreement between the numerical simulation results and the laboratory testing results was obtained. The error relative to the values obtained from the computer simulations for band curvature was 10–15% for the both rolling mills.

The discrepancies between the computer simulation results and the results obtained from the actual rolling process occurred due to the fact that the actual rolling process conditions differed from the ideal conditions existed during numerical simulations. In the real process, different friction conditions exist on the surface of contact between the metal and the working rolls. For the tests, new ground rolls were prepared, therefore the coefficient of friction on the metal–roll contact surface up to the moment of roll surface wear was lower than that adopted in the model. Moreover, the software program does not consider the layer of scale forming on the rolled specimen surface, which also influences the friction conditions.

In the real process, the distribution of temperature in the specimen volume is non-uniform, which is due to the design of the heating furnace, and specifically the furnace hearth, and the method of specimen supporting during heating.

### Conclusions

On the basis of the performed rheological tests of steel S355J2+N and the use of thus obtained results for modelling the rolling process, the following conclusions have been formulated:

- for the lowest strain rate of $\dot{\varepsilon}$ = 0.1 $s^{-1}$ and for the entire temperature interval of 800÷1000 °C, the value of flow stress initially increases and then, after exceeding a limiting strain, recovery processes predominate in the steel under investigation, and the shape of the $\sigma_p$–ε-curve becomes flat;
- during steel deformation at higher strain rates, i.e. $\dot{\varepsilon}$ = 1.0 and 10.0 $s^{-1}$, in the entire examined temperature interval of 800÷1000°C, the strain-hardening effects caused by cold work exceed the recovery processes and the work-hardening curves show a monotonic increase in all cases;
- the correctness of determining the rheological properties of steel for the conditions of the rolling process has an influence on the accuracy of results obtained from modelling of this process using the finite element method;
- a good agreement has been obtained between the results of numerical simulation of the rolling process and the results obtained in laboratory conditions; and
- the correct results obtained from the modelling studies will enable the asymmetric rolling process to be implemented in industrial conditions.

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