Journal of Achievements in Materials and Manufacturing Engineering

VOLUME 57
ISSUE 1
March
2013

Semi-industrial simulation of hot rolling and controlled cooling of Mn-Al TRIP steel sheets

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Received 12.01.2013; published in revised form 01.03.2013

Manufacturing and processing

ABSTRACT

Purpose: The aim of the work is a semi-industrial physical simulation of thermomechanical rolling and controlled cooling of advanced high-strength steels with increased Mn and Al content.

Design/methodology/approach: Four steels of various Mn and Nb concentration were thermomechanically rolled in 3 and 5 passes using a modern LPS line for physical simulation of hot rolling at a semi-industrial scale. The hot deformation course is fully automated as well as controlled cooling applied directly after finishing rolling. Temperature-time and force-energetic parameters of hot rolling were continuously registered and assessed.

Findings: The applied line consisting of two-high reversing mill, roller tables with heating panels, cooling devices and controlling-recording systems reflects industrial hot strip rolling parameters sufficiently. Reduction values and temperature-time regimes are similar to those used in industrial practice whereas strain rate is limited to about 10 s^{-1} what requires taking into account during comparison. All the steels investigated have high total pressure forces due to the high total content of alloying elements. The critical factor making it possible to obtain high-quality sheet samples with a thickness up to 3.3 mm is applying isothermal heating panels which decrease a cooling rate of thin sheets.

Research limitations/implications: The real complete simulation of hot strip rolling requires extension of a used line with a further module for simulation of continuous finishing rolling stages. The work is in progress.

Practical implications: The results can be successfully utilized in industrial hot rolling and controlled cooling practices after necessary modifications.

Originality/value: The efficient semi-industrial physical simulation of hot strip thermomechanical rolling of some new model AHSS grades containing increased Mn and Al content as well as Nb microadditions was presented.

Keywords: Thermomechanical processing; Hot rolling; Semi-industrial simulation; Physical simulation; Advanced high strength steel; Medium-Mn automotive steel

Reference to this paper should be given in the following way:
A. Grajcar, P. Skrzypczyk, D. Woźniak, S. Kołodziej, Semi-industrial simulation of hot rolling and controlled cooling of Mn-Al TRIP steel sheets, Journal of Achievements in Materials and Manufacturing Engineering 57/1 (2013) 38-47.

1. Introduction

Multiphase steels with retained austenite belong to advanced high-strength steels (AHSS), which are progressively used in the automotive industry. They include different ferrite-based grades covering a wide range of mechanical and technological properties. Their characteristic feature is the good combination of strength, ductility and technological formability [1-5]. At present, there is the tendency to further improve a strength-ductility range of steel sheets to satisfy the needs of the automotive market. Two main concepts can be distinguished in research presently carried out. The first one utilizes high-Mn alloys (18-30% Mn) characterized by fully austenitic microstructure, which show an exceptional strength-ductility balance [6-11]. They are under semi-industrial development due to technological problems related to their castability, hot-working, corrosion resistance and the high material cost. The second idea is to replace a ferritic matrix by bainite containing a large fraction of inter-lath austenite [12-19]. It is a relatively low-cost concept covering medium-Mn steels with strength above 1000 MPa and elongation from 15 to 30%.

AHSS and UHSS (Ultra High-Strength Steel) sheets are produced as cold-rolled followed by intercritical annealing or as hot-rolled followed by controlled cooling. A main problem for hot-rolled multiphase steel sheets is multi-step controlled run-out table cooling from a finishing hot rolling temperature to obtain a desired microstructure. Industrial trials are very expensive and rarely applied because of large scale of experimentation required and disturbances in normal production schedules [20-22]. Therefore, physical simulation of thermal cycles or thermomechanical schedules occurring during industrial processing is increasingly carried out. It offers the possibility of much faster and less expensive verification of a new technology than industrial experiments. Physical simulation is often realized by metallurgical process simulators (like Gleeble) using small samples and complex strain-temperature-time paths [6,17,23-31]. It is usually integrated with mathematical and numerical models describing the evolution of microstructure during hot-working and subsequent cooling [23-26,32,33]. A further step of physical simulation includes experiments carried out using laboratory technological lines equipped with rolling mills. It can be realized at a laboratory scale [23, 24] or at a semi-industrial scale when the rolling mills of higher force are applied [20,34,35]. Semi-industrial simulation reflects better real industrial conditions because of a high similarity scale. It means that applied parameter values of a process affecting product properties are similar to the values used in industrial conditions at much lower mass and experimental costs [20,34]. Results of the physical simulation of thermomechanical processing using a Gleeble device for a series of medium-Mn multiphase AHSS are given in [13,17,28]. The present work addresses their hot-working behavior during semi-industrial simulation trials.

2. Experimental procedure

2.1. Material

The paper presents the semi-industrial simulation of hot rolling and direct controlled cooling of four laboratory-melted high-strength Mn-Al steels with various Mn and Nb contents. The chemical composition of these medium-Mn steels is given in Table 1. The difference between Mn and Nb concentration is the basis for steel coding (3Mn, 3MnNb, 5Mn and 5MnNb). Manganese was used to stabilize austenite whereas the low-Si - high-Al concept was chosen to obtain carbide-free bainite. Mo and Nb were used to increase strength. Special attention was paid to compare the effect of Mn and Nb on the hot-working behaviour of investigated steels.

The ingots were produced by vacuum induction melting in the Balzers VSG-50 furnace at the Institute for Ferrous Metallurgy, Gliwice, Poland. Forging of the ingots was carried out at a temperature range between 1200 and 900°C to obtain 22x170 mm flat samples. After air cooling to room temperature the steels containing 3% Mn have bainitic-austenitic microstructures whereas martensite appears additionally in 5Mn steels as a result of their higher hardenability (Table 1).

2.2. Description of semi-industrial simulation line

Rough and thermomechanical rolling trials were carried out in the semi-industrial line (LPS) at the Institute for Ferrous Metallurgy in Gliwice, Poland (Fig. 1) [20,34]. The main modules of the line contain:

- electric resistance reheating furnace with maximum austenitizing temperature of 1400°C,
- two-high reversing hot rolling mill with roll diameter of 550 mm and roll barrel length of 700 mm,
- roller tables with isothermal heating panels, which were adjusted for 500°C (Fig. 2),
- air-blow and water-spray cooling devices,
- electric resistance furnace for heat treatment.

The description of additional devices of the semi-industrial line and their detailed parameters can be found in [20,34,35]. The line is fully automated and control of hot rolling is done with the use of the control desk (Fig. 3). The following values were measured and registered during hot rolling:

- thickness of strand,
- roll gap (distance between rolls unbiased and under load),
- rolling speed,
- rotational speed of rolls,
- temperature of strand at the input and at the output,
- roll force under each adjusting screw and total roll force,
- roll torque on each coupling spindle and total roll torque,
- time of a pass,
- time between passes.

Parameters of hot rolling were established assuming that the amount of stain applied is conditioned by an acceptable pressure force of a strip on the rolls. Determination of the mean unique pressure is a basis of the assigning a pressure force during rolling. Correct description of this parameter for specific conditions always consists in the selection of a method suitable for a given process. For the rolling mill used, the determination of the mean unit pressure exerted by a strip on the rolls is efficient when the Zjuzin method is applied [36].

Table 1.
Chemical composition of the investigated steels (mass content, %) and the initial microstructure

Steel grade	C	Mn	Al	Si	Mo	Nb	S	P	N	Microstructure
3Mn	0.17	3.3	1.7	0.22	0.23	-	0.014	0.010	0.0043	Bainitic-austenitic
3MnNb	0.17	3.1	1.6	0.22	0.22	0.04	0.005	0.008	0.0046	Bainitic-austenitic
5Mn	0.16	4.7	1.6	0.20	0.20	-	0.004	0.008	0.0039	Bainitic-martensitic
5MnNb	0.17	5.0	1.5	0.21	0.20	0.03	0.005	0.008	0.0054	Bainitic-martensitic

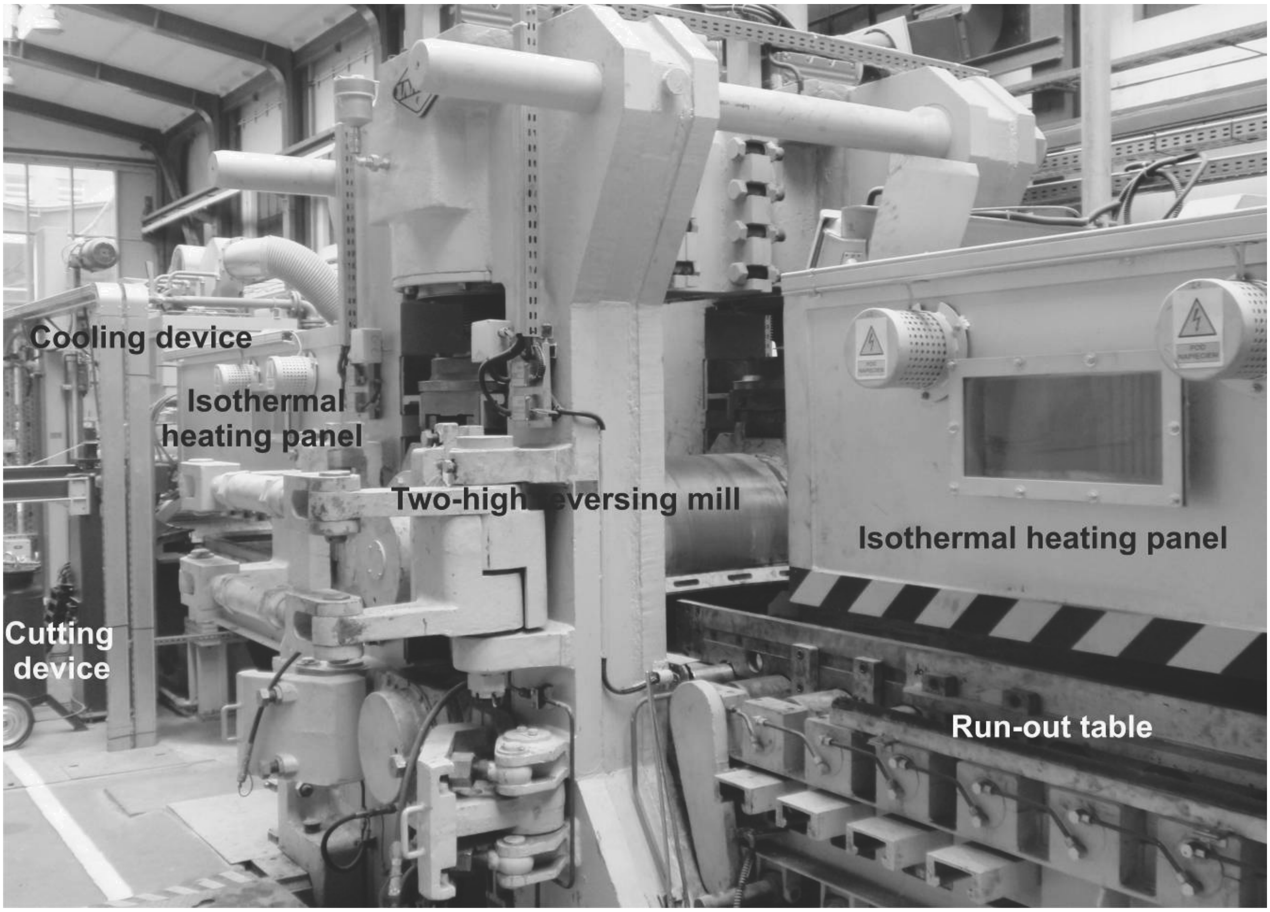

Fig. 1. Semi-industrial line for simulation of hot rolling and controlled cooling of sheets and bars at the Institute for Ferrous Metallurgy in Gliwice, Poland

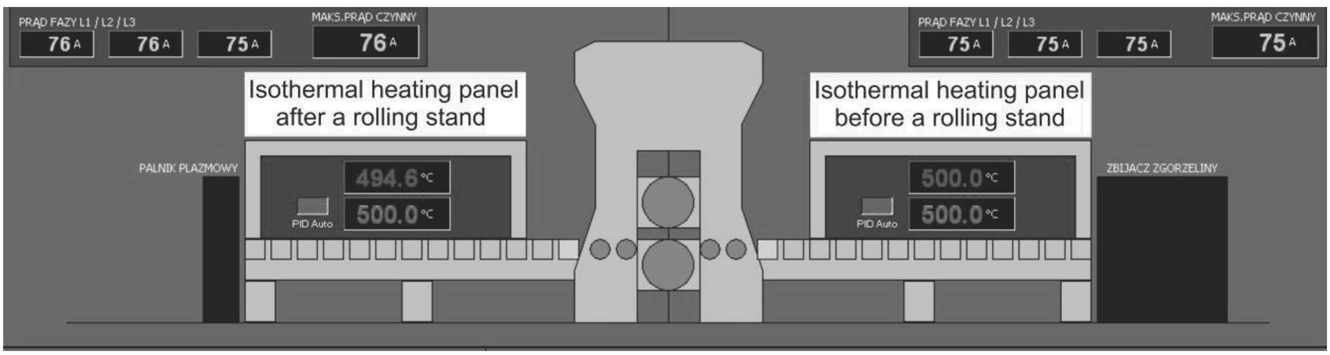

Fig. 2. Schematic of isothermal heating panels before and after a rolling stand

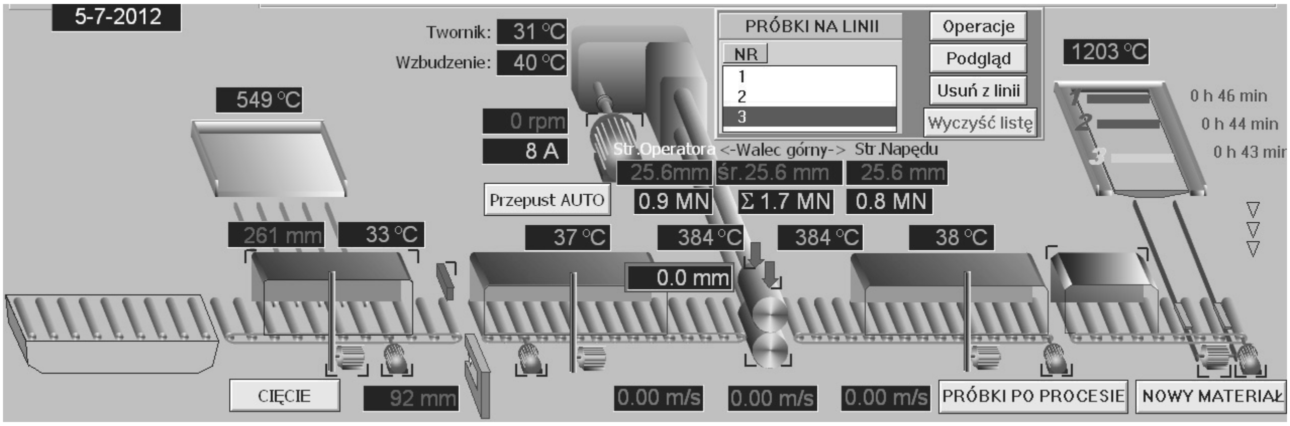

Fig. 3. View of the all modules of the semi-industrial rolling line from the control desk

The temperature was measured automatically before and after a rolling stand using pyrometers being a permanent equipment of the line. Additionally, the final rolling temperature was measured using a portable pyrometer (Raytek - Raynger 3i1M).

Rough rolling of 22x170x400 mm flat samples was carried out in four passes into an intermediate thickness of about 9 mm at a temperature range between 1200 and 950°C. Then, the sheets were air-cooled to room temperature (Fig. 4).

3. Designing of thermomechanical rolling schedules

Reheating temperature of 1200°C was chosen on the basis of hot-ductility properties of steels taking into account their chemical composition. The flat samples were located in a furnace in the way enabling their thermal homogeneity. The temperature deviation between surface and core regions according to the furnace characteristic was lower than 2 °C. Austenitizing time was equal to 25 min. for rough rolling and 12 min. for thermomechanical rolling of flat samples with a thickness of 9 mm. Thermomechanical processing consisted in hot rolling of 9 mm thick samples into a final thickness in 3-pass or 5-pass rolling. The obtained sheets were controlled cooled by the use of auxiliary devices directly after finishing rolling. The finishing rolling temperature (T_{FR}) was selected on the basis of earlier plastometric and dilatometric investigations [13,17,28]. It is about:

- 850°C for strips hot-rolled in 3 passes - A designation
- 750°C for strips hot-rolled in 5 passes - B designation.

The whole process including main parameters of rough and thermomechanical rolling is illustrated in Fig. 4. Time from the reheating furnace to the first pass was equal to about 20 s and the time between successive passes was from 7 to 15 s. Figure 4a presents the schematic of hot deformation and controlled cooling for the steels containing 3% Mn hot-rolled in passes. After finishing rolling at about 850°C sheet samples were slowly cooled within 15 s using the isothermal heating panel (adjusted to 500°C - Fig. 2) to a temperature of about 700°C. Then, the controlled mixed air-blow and water-spray cooling devices were applied to lower a sample temperature to 400°C. The mean cooling rate of about 27°C/s was used, which was determined during test trials. The sheets were isothermally held in the furnace at 400°C for 300 s to enrich austenite in carbon. A final step was air cooling of sheet samples to room temperature. A cooling path was very similar for the sheet samples hot-rolled in 5 passes except the time of slow cooling under heating panels, which was shortened to 5 s (Fig. 4b). The 5Mn and 5MnNb steels were cooled to a holding temperature using the air-water spray directly from 850°C for the samples rolled in 3 passes (designation A) or from about 750°C when 5-pass rolling was applied (Fig. 4c - designation B).

The following coding has been applied in the present work for the identification of different variants of the thermomechanical processing:

- 3Mn-A - 3Mn steel sheet deformed in 3 passes with the finishing rolling temperature of about 850°C,
- 3MnNb-A - 3MnNb steel sheet deformed in 3 passes with the finishing rolling temperature of about 850°C,
- 3Mn-B - 3Mn steel sheet deformed in 5 passes with the finishing rolling temperature of about 750°C,
- 3MnNb-B - 3MnNb steel sheet deformed in 5 passes with the finishing rolling temperature of about 750°C,
- 5Mn-A - 5Mn steel sheet deformed in 3 passes with the finishing rolling temperature of about 850°C,
- 5MnNb-A - 5MnNb steel sheet deformed in 3 passes with the finishing rolling temperature of about 850°C,
- 5Mn-B - 5Mn steel sheet deformed in 5 passes with the finishing rolling temperature of about 750°C,
- 5MnNb-B - 5MnNb steel sheet deformed in 5 passes with the finishing rolling temperature of about 750°C.

Calculated parameters of hot rolling required for loading to a controlling program are listed in Tables 2 and 3 - respectively for the 3-pass and 5-pass rolling. These parameters were designed according to the criteria of physical similarity at modelling of hot-working processes, i.e. thermal similarity, friction similarity and strengthening similarity [35]. It is obvious that a major problem of assuring of the thermal similarity is faster cooling of thin sheet samples compared to industrial sheets of higher thermal capacity. The deviation was minimized by appplying isothermal panels heated to 500°C, which decrease a cooling rate of sheet samples contacting with roller-tables

(Fig. 2). The desired deformation values between 30 and 24% and corresponding logarithmic strain values are very similar to that used in industrial hot strip rolling. Rooling speed is lower than 1 m/s (Tables 2 and 3) because of safety reasons in semi-industrial lines [34,35]. The corresponding strain rate progressively increases to about 10s^{-1} but it is lower compared to industrial trials. It should be taken into account during the interpretation of results.

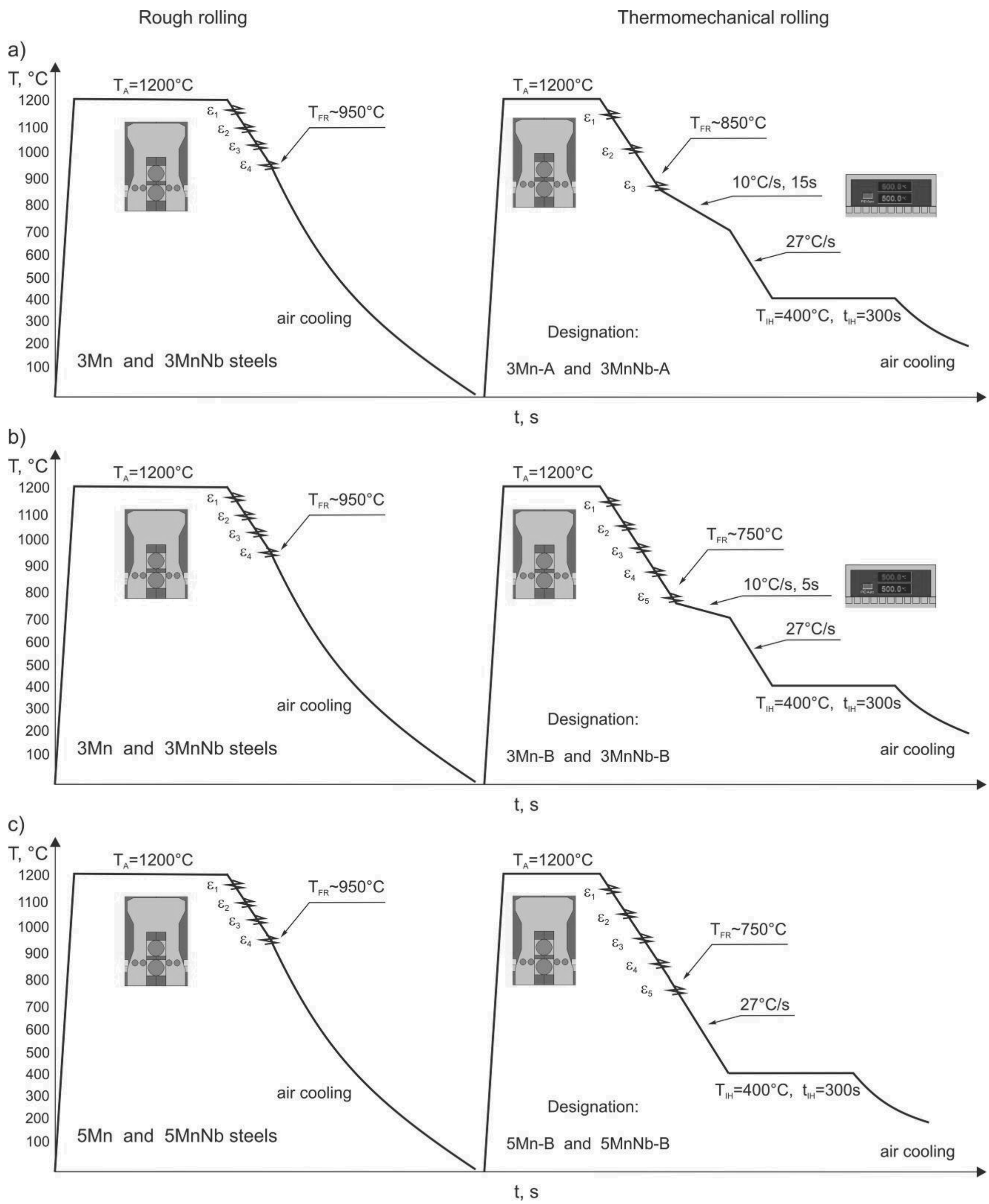

Fig. 4. Rough rolling paths and subsequent thermomechanical processing schedules designed for hot rolling of 9 mm thick steel sheets in 3 passes (a) and in 5 passes (b, c) for 3Mn and 3MnNb steels (a, b) and 5Mn and 5MnNb steels (c)

Table 2.
Calculated parameters of the thermomechanical rolling in 3 passes

Pass number	Deformation value, %	Elongation	Logarithmic strain	Strain rate, s^{-1}	Rolling speed, ms^{-1}
1	29.4	1.41	0.34	4.8	0.6
2	30.0	1.42	0.35	6.7	0.7
3	23.8	1.31	0.27	8.1	0.8

Table 3.
Calculated parameters of the thermomechanical rolling in 5 passes

Pass number	Deformation value, %	Elongation	Logarithmic strain	Strain rate, s^{-1}	Rolling speed, ms^{-1}
1	29.4	1.41	0.34	5.5	0.7
2	30.0	1.42	0.35	6.7	0.7
3	26.2	1.35	0.30	7.4	0.7
4	25.8	1.35	0.30	8.6	0.7
5	26.1	1.35	0.30	10.0	0.7

Table 4.
Measured and calculated parameters of the thermomechanical rolling of 4.5 mm thick sheet samples in 3 passes from 8.5 mm thick charge

Pass number		Sheet thickness after pass, mm	Deformation value, %	Logarithmic strain	Strain rate, s^{-1}	Rolling speed, ms^{-1}
Charge	3Mn-A	8.5		-		
	3MnNb-A	9.0				
	5Mn-A	8.5				
	5MnNb-A	8.5				
1	3Mn-A	6.5	23.5	0.27	5.0	0.63
	3MnNb-A	6.6	26.7	0.31	5.3	0.63
	5Mn-A	6.8	20.0	0.22	4.6	0.63
	5MnNb-A	6.3	25.9	0.30	5.4	0.63
2	3Mn-A	5.4	16.9	0.19	5.6	0.74
	3MnNb-A	5.5	16.7	0.18	5.5	0.74
	5Mn-A	5.5	19.1	0.21	5.8	0.73
	5MnNb-A	5.3	15.9	0.17	5.4	0.73
3	3Mn-A	4.5	16.7	0.18	6.9	0.84
	3MnNb-A	4.7	14.5	0.16	6.3	0.84
	5Mn-A	4.5	18.1	0.20	7.2	0.85
	5MnNb-A	4.6	13.2	0.14	6.0	0.84

4. Results and discussion

Real reduction values applied during 3-pass rolling gathered in Table 4 are lower than the initially calculated ones (Table 2). It is related to the limitation of a maximum pressure force of the rolling mill used [34]. The relative amount of deformation for the first pass is equal from 20 to 27% and decreases for successive deformation stages. It is between 13 and 18% for a final pass. This reduction range is similar to that used in industrial processes. On the other hand, strain rate values increase from 5 to 7 s^{-1}, what is in good accordance with the calculated values. The applied reduction sequence allows to obtain 4.5 mm thick sheets samples with good flatness, surface quality and without edge tear (Fig. 5). The thickness of Nb-microalloyed steel sheets is slightly higher due to lower true stain applied in the final pass (Table 4).

Relative reduction and corresponding true strain values of 5-pass rolling are comparable to those of 3-pass rolling except the first pass for which the smaller amount of deformation was applied (Table 5). The final reduction value is also lower (true strain = 0.14) because of the low finishing rolling temperature. The true strain values successively decrease whereas the strain rate increases gradually from 4 to 9 s^{-1}. A final sheet thickness is about 3.3 mm.

The high deformation resistance and subsequent relatively small reduction values are a result of high flow stresses of investigated steels. The flow stress values registered during four-step physical simulation of finishing hot rolling in laboratory conditions using a Gleeble simulator at a temperature range between 1150 and 850°C amount from 120 to 270 MPa, being slightly higher for Nb-microalloyed steels [17,28]. This is due to the relatively high content of Mn, Al, Si and Mo, which is equal to about 5 and 7 wt.% - respectively for 3Mn/3MnNb and 5Mn/5MnNb steels.

Table 5.
Measured and calculated parameters of the thermomechanical rolling of 3.3 mm thick sheet samples in 5 passes from 8.5 mm thick charge

Pass number		Sheet thickness after	Deformation value,	Logarithmic strain	Strain rate,	Rolling speed,
Charge	3Mn-B	8.5	-			
	3MnNb-B	9.0				
	5Mn-B	8.5				
	5MnNb-B	8.5				
1	3Mn-B	7.0	17.6	0.19	4.2	0.63
	3MnNb-B	7.1	21.1	0.24	4.5	0.63
	5Mn-B	7.1	16.5	0.18	4.0	0.62
	5MnNb-B	6.9	18.8	0.21	4.4	0.63
2	3Mn-B	5.7	18.6	0.20	5.7	0.74
	3MnNb-B	5.7	19.7	0.22	5.8	0.74
	5Mn-B	5.8	18.3	0.20	5.5	0.73
	5MnNb-B	5.6	18.8	0.21	5.7	0.74
3	3Mn-B	4.7	17.5	0.19	6.9	0.84
	3MnNb-B	4.6	19.3	0.21	7.3	0.84
	5Mn-B	4.8	17.2	0.19	6.8	0.85
	5MnNb-B	4.6	17.8	0.20	7.0	0.84
4	3Mn-B	3.9	17.0	0.19	8.4	0.95
	3MnNb-B	3.8	17.4	0.19	8.6	0.95
	5Mn-B	3.9	18.7	0.21	8.8	0.95
	5MnNb-B	3.8	17.0	0.19	8.6	0.95
5	3Mn-B	3.4	12.8	0.14	7.8	0.95
	3MnNb-B	3.3	13.1	0.14	8.1	0.95
	5Mn-B	3.4	12.8	0.14	7.8	0.94
	5MnNb-B	3.3	13.1	0.14	7.6	0.89

Fig. 5. Strips of 4.5 mm thickness thermomechanically rolled in 3 passes

Generally, flow stress values increase in successive passes because of decreasing hot-working temperature and increasing strain rate values. Sometimes, the lowering of flow stress takes place due to recrystallization induced by accumulated strain or the uncontrolled presence of ferrite during finishing rolling. The latter case can happen in steels containing high Al content, which is a strong ferrite-forming element [37]. This can lead to uncontrollable variation in tension, friction, rolling forces and mass flow [22]. However, flow stress values are not always clear reflected by changes in the rolling force observed in hot strip mills. Deformation schedules of finishing rolling in conventional hot strip mills are commonly set up so as to evenly distribute the drive motor loads between the finishing stands, resulting in progressive decrease of rolling forces [22]. The total pressure force for the investigated 3- and 5% Mn steels covers a near stable range between 0.84 and 1.15 MN for the thermomechanical processing with 3 passes (Table 6). The total pressure force during 5-pass rolling was comparable for the first four deformation steps and gained near 1.3 MN. A result of the small reduction at a final pass is lowering the pressure force to about 0.65 MN. The hot rolling with near constant pressure force ensures the stability of a hot deformation process. As the example, the Figure 6 presents the registration of the total pressure force for a 5Mn-A steel strip hot-rolled in three passes.

Changes in the temperature of sheet samples hot-rolled in 3 passes are listed in Table 6. After the first pass the temperature decreases to about 950°C because of 20 s needed for the transfer of test pieces from a reheating furnace to a rolling stand and the heat consumed by rolls of high thermal capacity. The temperature measured after the second rolling stand is 900°C and after a final pass it amounts to about 820°C (Table 6). For example, the temperature values registered for the 5Mn-A steel sheet after the third pass by stationary pyrometers are presented in Fig. 7. It should be taken into account that measured temperature values can be lower than real values in a central part of sheets due to the presence of scale on strip surfaces.

Table 6.
Measured total pressure force values and temperature-time parameters of the thermomechanical rolling of 4.5 mm thick sheet samples in 3 passes from 8.5 mm thick charge

Pass number	Steel grade	Total pressure force, MN	Temperature of sheet surface after the pass, s	Time of the pass, s	Time between passes, s
1	3Mn-A	0.98	950	1.3	-
	3MnNb-A	0.96	951	1.3	-
	5Mn-A	0.98	953	1.5	-
	5MnNb-A	0.84	932	1.6	-
2	3Mn-A	1.15	889	1.4	12.3
	3MnNb-A	1.13	890	1.3	12.0
	5Mn-A	1.11	908	1.6	10.0
	5MnNb-A	1.04	885	1.7	10.1
3	3Mn-A	1.13	814	1.4	11.7
	3MnNb-A	1.13	818	1.4	11.3
	5Mn-A	1.12	828	1.7	9.6
	5MnNb-A	1.09	826	1.7	10.4

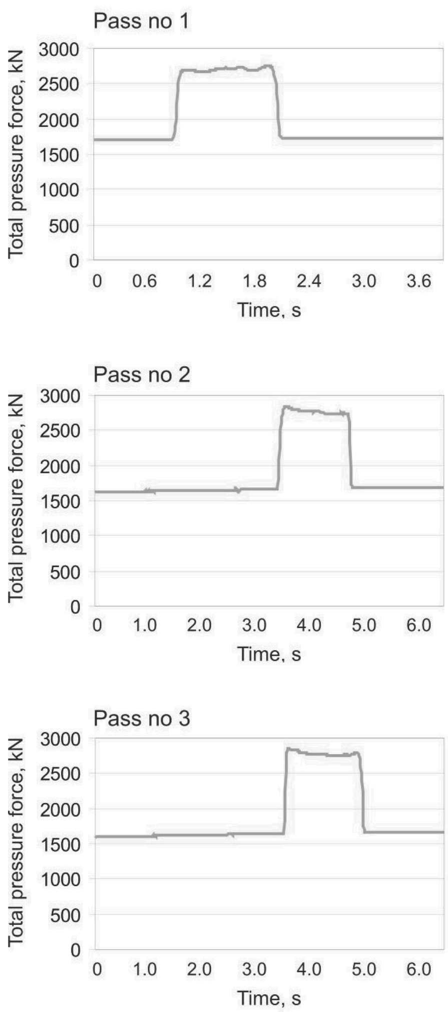

Fig. 6. Registration of the total pressure force for the 5Mn-A steel strip hot-rolled in three passes

The temperature value measured directly after finishing the 3-pass rolling using a portable pyrometer is about 850°C, what is 30°C higher. The finishing deformation temperature of 5-pass rolling is about 750°C. It is a reason of the relatively small reduction value applied in a final pass. Preliminary results of microstructure investigations obtained for these simulation schedules are presented in [38].

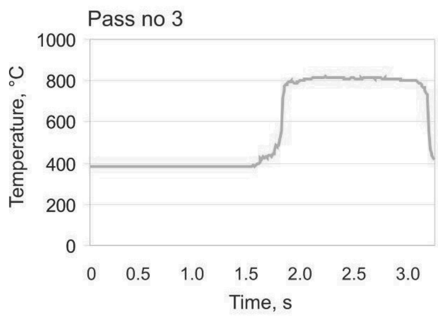

Fig. 7. Temperature values registered on a surface of 5Mn-A steel sheet after the third pass by a stationary pyrometer

5. Conclusions

It has been proved that the used LPS line consisting of two-high reversing mill, roller tables with isothermal heating panels, cooling devices and controlling-recording systems enables the efficient semi-industrial simulation of hot strip rolling of an advanced group of AHSS steels dedicated for automotive industry. Continuous registration of force-energetic parameters of hot rolling makes it possible to effectively measure pressure forces and estimate deformation resistance. It was shown that the stable 3-pass and 5-pass thermomechanical rolling is possible at total pressure forces near 1.3 MN. The pass temperatures, reduction values and time parameters applied reflect industrial conditions satisfactory. Increasing the manganese content from 3 to 5% and microaddition of Nb do not influence the hot deformation process in a meaningful way. Applying isothermal panels located at both sides of a rolling stand decreases effectively a cooling rate of hot-rolled strips and enables to obtain a high surface quality sheet samples with a thickness of 4.5 mm and 3.3 mm - respectively for the 3-pass rolling with a finishing deformation temperature of about 850°C and 5-pass rolling with a finishing rolling temperature of about 750°C.

Acknowledgements

The work was partially supported by the Polish Ministry of Science and Higher Education in a period of 2010-2012 in the framework of project No. N N508 590039.

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