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Rolling of ingots of third-generation high-strength steels into sheets

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Abstract. One of the essential branches of today's engineering production involves the production of sheet stock by rolling. In the automotive industry is used the majority of steel sheet stock. In recent decades, this sector has been striving to reduce vehicle emissions. One of the available solutions involves the use of advanced high-strength steels whose chemical composition and strengthening mechanisms make it possible to build the car body with thinner sheet blanks than before. For rolling trials in which ingots were converted into 1.8 mm sheet by combined hot and cold rolling were used two advanced high-strength steels containing 0.2 wt. % carbon and additions of manganese, silicon and different levels of aluminium. This procedure was found to produce strengths in excess of 1000 MPa combined elongation of more than 15 %.

1 Introduction

Steel stock is often rolled into flat sheet or products of more or less complex shapes. Parts with a simple geometry include various shaped sections or tubes with different cross sections. In lightweight structures, such as front or rear crumple zones of vehicles, including bumpers, more intricate rolled products are often used [1, 2]. Rolled stock and products are often formed into vehicle frame structures. Their materials are high-strength steels [1, 3]. Third generation of high-strength steels combines several types of reinforcement mechanisms, mainly TRIP (Transformed induced plasticity) and TWIP (Twinning induced plasticity) and alloying with manganese, silicon and aluminum [1-3]. Thanks to mechanical properties of these steels, designers can use thinner sheet for making equal components. This translates into cost savings, in terms of both materials and energy, as the weight of parts and fuel consumption are reduced [1, 3, 4]. Because the primary use of high-strength steels is the manufacture of safety components of vehicle body, there is a need to study the entire process of sheet production and not only the manufacture of the shaped part [5]. During hot and cold rolling of ingots, a number of problems may arise, prohibiting the production of high-quality defect-free sheet with a desired microstructure. This paper discusses rolling of small ingots into 1.8 mm sheets of newly-designed experimental high-strength steels with different manganese to aluminium ratio.

2 Experimental program

Two advanced high-strength steels identified as C3Mn1.4Al and C3Mn2Al with different aluminium levels were designed for this series of experiments. This enabled the effects of the manganese-aluminium ratio on microstructure evolution and mechanical properties to be studied. The main alloying additions in C3Mn1.4Al were manganese, silicon and aluminium (table 1). The only difference in the composition of the second material, C3Mn2Al, was a higher aluminium content: 2 % (table 1). Measurement in a dilatometer was employed to find heating and forming temperatures with dilatometer SG instruments L75PT with argon atmosphere. Heating to the temperature 600 °C was 10 °C/min, then the heating rate dropped to 3 °C/min to the temperature 1000 °C. Austenitizing temperatures for C3Mn1.4Al and C3Mn2Al were 961 °C and 1025 °C. The heating temperature of 1050 °C was chosen based on the dilatometer data and empirical findings. The materials were cast into 50 kg ingots. They were rolled in a combined rolling mill at the company COMTES FHT, where a two-high stand for hot rolling and four-high stand for cold rolling are available.

Table 1. Chemical composition of the experimental materials.

	C	Si	Mn	P	S	Cr	Al
C3Mn1.4Al	0.22	0.59	3.06	0.008	0.003	0.19	1.45
C3Mn2Al	0.22	0.56	3.13	0.008	0.003	0.17	2.02

2.1 Hot rolling

Prior to hot rolling were the top and bottom of the ingots removed. The ingots were placed into a pre-heated furnace at 1050 °C for 2 hours. Then they were transferred from the furnace to the rolling mill. The rolling sequence consisted of nine successive reductions with no reheating operation. The initial diameter was 97 mm and the final thickness of the strip was 13 mm (figure 1a). The temperature at the entry was about 1035 °C and temperature did not dropped below 950 °C during all reductions. With each reduction, the rolling force increased: from the initial 680 kN to 2000 kN in the last reduction. No excessive buildup of force, irregular thickness or waviness were experienced in the rolling process. Immediately after finish rolling to 13 mm, the rolled part was cut into three identical segments 800 mm in length (figure 1b) and reheated in a furnace for 1 hour.

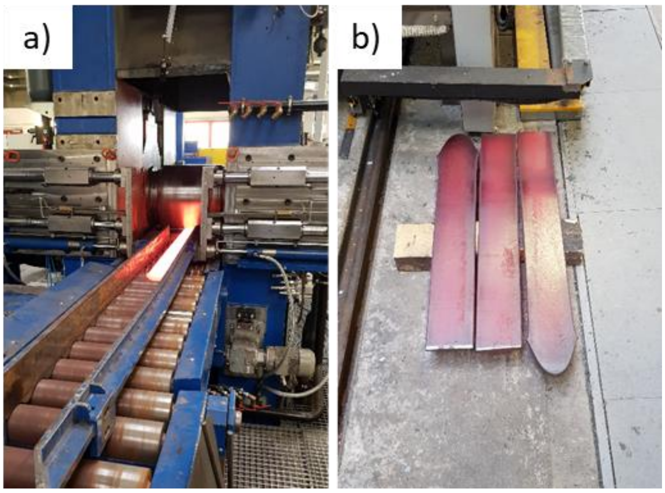

Figure 1. Rolled product passing through the rolling mill (a); rolled product 13 mm in thickness cut into three parts (b).

Subsequent hot rolling involving four reductions to the final stock thickness of 5.2 ± 0.1 mm. Rolling force varied from 1060 kN in the first reduction to 2000 kN in the last pass. Over the course of the rolling process, temperature decreased from the initial 1050 °C to 850 °C in the last reduction. After this step, no defects were found in the materials. After rolling, the rolled product was cut into three segments approximately 480 mm in length. The segments then cooled in air to room temperature. The segments were annealed at 680 °C for one hour before cold rolling.

2.2 Cold rolling

Following the in-process annealing at 680 °C, both sides of the rolled products were ground to remove scale and poor-quality surface (figure 2a). The rolling stand was changed over to a four-high mill for cold rolling (figure 2b). The materials were rolled to the final thickness of 1.8 ± 0.1 mm. As the ability of the material to undergo plastic deformation had not been depleted by cold rolling, there was no need for additional in-process annealing. The cold-rolled products were normalized. The normalizing sequences for C3Mn1.4Al and C3Mn2Al were 1000 °C/1.5 hr and 950 °C/1.5 hr, respectively. Finally, the rolled sheets were straightened and ground to the desired thickness (1.5 mm) for subsequent processing.

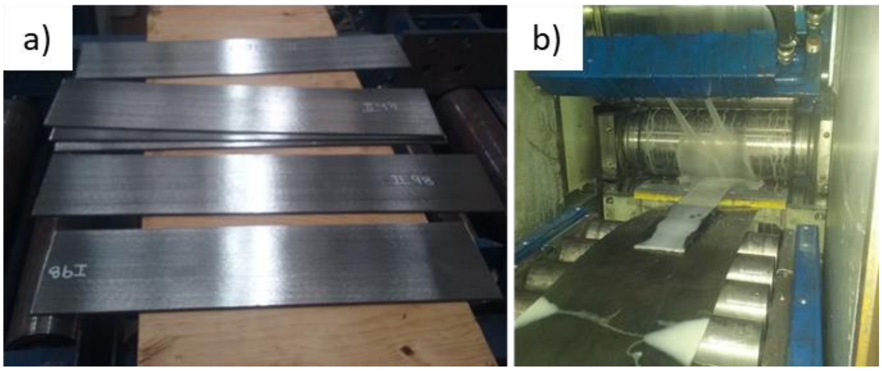

Figure 2. Ground rolled products (a), cold rolling process (b).

3 Results and Discussion

3.1 Microstucture analysis

Hot-rolled microstructures were examined under a light microscope. The structure contained distinct strain bands which are typical of rolling. The microstructure of C3Mn1.4Al consisted of martensite and bainite. Hardness was 470 HV10 (figure 3a). C3Mn2Al, which had a higher aluminium content, contained a predominantly martensitic-bainitic microstructure as well. It was coarser than in the other material. In addition, there were notable bands of free ferrite. They were the result of chemical heterogeneity and the shift of the ferrite nose towards faster cooling rates caused by the higher aluminium content. The presence of ferrite affected hardness, the value of which was 419 HV10 (figure 3b).

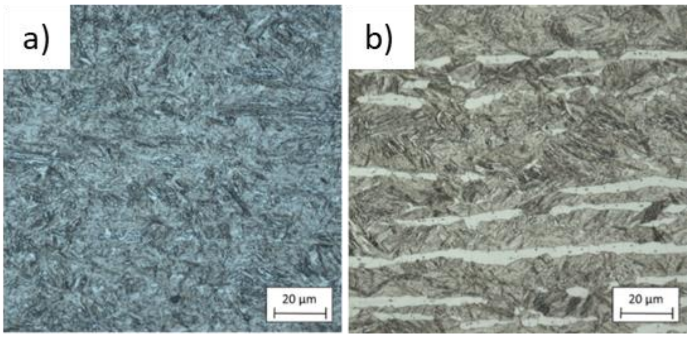

Figure 3. Micrographs of C3Mn1.4Al (a) and C3Mn2Al (b) after hot rolling.

Hot rolling was followed by in-process annealing at 680 °C for one hour. The final microstructures were heavily tempered (figure 4). Dense cementite and carbide precipitates were found along the boundaries of poorly-visible martensite laths. There was a drop in hardness of C3Mn1.4Al and C3Mn2Al to 250 HV10 and 264 HV10, respectively.

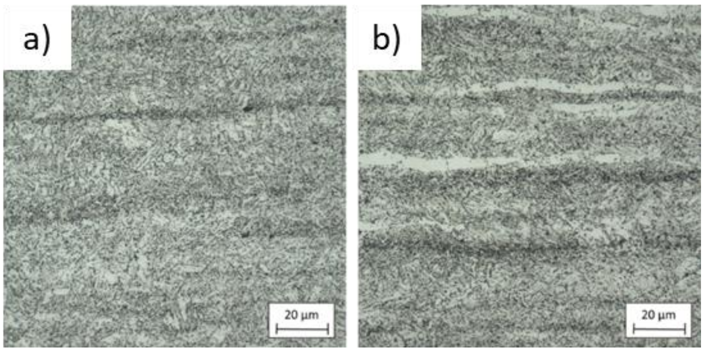

Figure 4. Micrographs of C3Mn1.4Al (a) and C3Mn2Al (b) after in-process annealing.

The resulting microstructures of C3Mn2Al and C3Mn1.4Al were consistent with the appearance of cold-rolled structures (figure 5). They contained a fine mixture of ferrite and cementite produced by tempering. C3Mn2Al also contained conspicuous deformation bands consisting of ferrite. By comparison, the width of the deformation bands was different in each material. In addition, there were more impurities in C3Mn2Al than in C3Mn1.4Al.

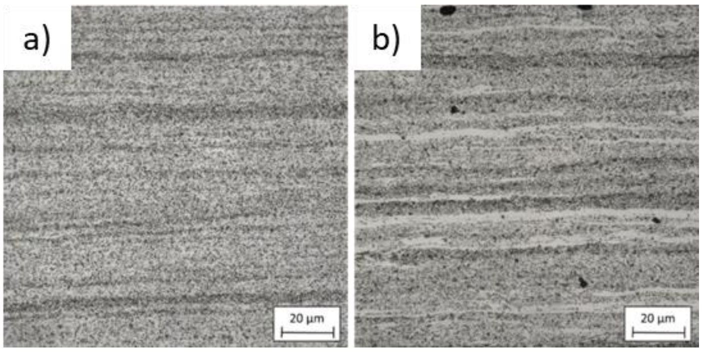

Figure 5. Micrographs of cold-rolled C3Mn1.4Al (a) and C3Mn2Al (b).

3.2 Mechanical properties

Mechanical properties were assessed by means of tensile tests. Flat test specimens were used, in which the gauge section was 10×1.5 mm in cross section and 50 mm in length (figure 6). In order to characterize anisotropy in the sheet stock, some specimens were oriented parallel to the rolling direction and the rest perpendicularly to the rolling direction. After hot rolling, the mechanical properties in both materials were favourable. C3Mn1.4Al showed an ultimate strength of just above 1500 MPa and elongation of 20 % in the rolling direction. The ultimate strengths in the perpendicular direction were nearly equal. Elongation was slightly lower, just under 18 % (table 2). In C3Mn2Al, which had a higher aluminium content, the ultimate strength was 100 MPa less: 1400 MPa. Elongations in the rolling direction and crosswise were just under 18 % and below 15 %, respectively (table 3). Higher aluminium content led to a lower ultimate strength and equal elongation.

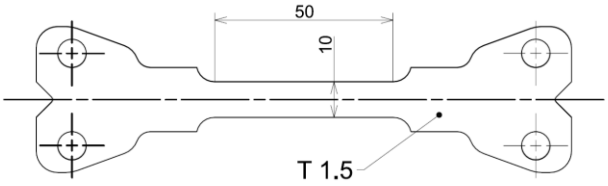

Figure 6. Drawing of the tensile test specimen.

Table 2. Results of mechanical testing of hot-rolled material.

	Offset yield strength ($R_{p0.2}$) [MPa]	$R_{p0.2}$ standard deviation	UTS (R_m) [MPa]	R_m standard deviation	A_{20mm} [%]	A_{20mm} standard deviation
C3Mn1.4Al	1089	12	1523	15	20.1	1.0
C3Mn1.4Al-90°	1119	12	1556	3	17.7	0.4
C3Mn2Al	1019	7	1423	10	18.3	0.2
C3Mn2Al – 90°	1010	3	1418	2	14.7	1.2

Annealing at 680 °C for one hour, which followed the hot rolling operation, led to a notable decrease in ultimate strength. In C3Mn1.4Al, the strength was around 810 MPa and elongation reached 28 % (table 3). In the other material, strength dropped to 770 MPa, while elongation rose to 31 % (table 3). The comparison between them shows that higher aluminium content was manifested in higher elongation and reduced yield strength and ultimate strength.

Table 3. Results of mechanical testing of hot-rolled material and in-process annealed material.

	Offset yield strength ($R_{p0.2}$) [MPa]	$R_{p0.2}$ standard deviation	UTS (R_m) [MPa]	R_m standard deviation	A_{20mm} [%]	A_{20mm} standard deviation
C3Mn1.4Al	704	15	806	0	31.0	0.8
C3Mn1.4Al-90°	717	3	811	2	30.0	1.0
C3Mn2Al	630	3	773	2	34.1	0.6
C3Mn2Al – 90°	620	2	779	4	30.0	0.3

In both cold-rolled materials, ultimate strength in the rolling direction was approximately 1100 MPa and elongations were low, 3-5 % (table 4). Perpendicular to the rolling direction, ultimate strengths were approx. 100 MPa higher: 1200 MPa. After cold rolling, both materials showed similar properties. C3Mn1.4Al exhibited higher ultimate strength and yield strength, by mere units of MPa.

Table 4. Results of mechanical testing of cold-rolled material.

	Offset yield strength ($R_{p0.2}$) [MPa]	$R_{p0.2}$ standard deviation	UTS (R_m) [MPa]	R_m standard deviation	A_{20mm} [%]	A_{20mm} standard deviation
C3Mn1.4Al	1022	8	1119	14	5.2	0.05
C3Mn2Al	999	4	1100	3	4.9	0.30
C3Mn1.4Al – 90°	1036	0.2	1203	11	4.5	0.20
C3Mn2Al – 90°	1025	3	1193	2	3.2	0.14

For the purpose of restoring the plastic deformation ability of the material, normalizing annealing was performed. The normalizing sequences for C3Mn1.4Al and C3Mn2Al were performed at 1000 °C and 950 °C/1.5 hr, respectively. The annealing operation greatly improved elongation values without altering ultimate strength in both materials. In the rolling direction, elongations in excess of 15 % were obtained, and those perpendicular to the rolling direction were 10 % (table 5).

Table 5. Mechanical properties after rolling to final dimension and normalizing.

	Offset yield strength ($R_{p0.2}$) [MPa]	$R_{p0.2}$ standard deviation	UTS (R_m) [MPa]	R_m standard deviation	A_{20mm} [%]	A_{20mm} standard deviation
C3Mn1.4Al	1041	12	1099	4	16.3	1.4
C3Mn1.4Al-90°	1026	0.2	1174	2	11.2	0.8
C3Mn2Al	1004	15	1064	9	15.0	0.6
C3Mn2Al – 90°	1017	5	1144	4	8.6	0.1

4 Conclusion

Newly-designed third-generation high-strength steels with higher manganese levels than classical TRIP steels were used for an experimental procedure, in which ingots were rolled into 1.8-mm sheet. Based on known phase transformations and results of earlier research, appropriate soaking temperatures and reductions in hot and cold rolling were proposed. Using this manufacturing procedure, sheet stock free from internal defects was obtained. Cold rolling and normalizing led to ultimate strengths between 1000 and 1100 MPa and elongations up to 16 %. The higher aluminium level in C3Mn2Al was reflected in a slightly lower ultimate strength. In this steel, distinctive ferrite bands and higher levels of impurities were found in final state. The data collected in the process of rolling of ingots into sheet stock was crucial for mapping the initial condition of the multiphase high-strength steels.

Acknowledgement

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References

[1] Demeri M Y 2013 *Advanced high-strength steels: Science, Technology and Applications,* Materials Park, Ohio ASM International.

[2] Tamarelli C M 2011 *AHSS 101: The Evolving Use of Advanced High-Strength Steels for Automotive Applications,* Southfield, Michigan.

[3] Rowe J 2012 *Advanced Materials in Automotive Engineering,* ed. Rowe J, Elsevier Amsterdam, Netherlands.

[4] Chen S C et al., 2019 Microstructure and mechanical bevaiors of GPa-grade TRIP Steels Enabled by hot-rolling processes *Materials Science & Engineering,* A **761.**

[5] Kučerová L, Jirková H and Mašek B 2014 The Effect of Alloying on Mechanical Properties of Advanced High Strength Steels *Archives of Metallurgy and Materials* **59** 1189-92.