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INDUSTRIAL RESEARCH IN THICKER HEAVY PLATES (70-80 MM) HSLA STEEL MICRO-ALLOYED WITH Mo-Nb-Ti THERMO-MECHANICAL CONTROL PROCESS IN ARCELORMITTAL GALATI

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ABSTRACT

Thermomechanical rolling (TMR or TMCP) is a special rolling process resulting in an extremely high-strength, fine-grained substructure which simultaneously offers very good toughness and cold formability. TM products have much lower carbon content and consequently are much less susceptible to cold cracks during welding. In ArcelorMittal Galati the challenge was to increase for structural steel the feasibility from 50 up to 80 mm and targeted plate thickness without ACC mode. Slabs thickness produced in AMG with maximum 250 mm thickness corresponding to almost the maximum ratio of 3:1 between slabs and targeted plate thickness according to the EN 10025/4/2004. TM rolled steels performed in industrial trial presented in this paper were performed in Heavy Plate Mill no 2 in ArcelorMittal Galați using computer process SIROLL assisted by AGC system. The main goal of this experimental rolling is to provide a concise and complete overview of the rolling process with higher amount of deformation below T_{nr} *(non-recrystallisation temperature) and close to* A_{r3} *in austenite region, and to address the potential to optimize it.*

KEYWORDS: thermomechanical steel, thicker heavy plates, 70 mm, 80 mm, T_{nr}

Nomenclature:

B: flat background
c: sound velocity
α: scattering angle
T: fitting parameter for a constant radial temperature gradient

1. Introduction

In a world in continuous competition it is a challenge to perform higher strength steel like HSLA [1, 9, 10] (higher strength low alloyed). Usual thicker heavy plates over 30 mm thickness are produced by the most important players on the market steel in TMR [2] mode (thermo-mechanical control process) followed by ACC mode (accelerated control cooling). In ArcelorMittal Galati we managed to produce thicker plates up to 50 mm without ACC [3] mode for structural steel. Now, the challenge was to increase the feasibility up to 80 mm corresponding to almost the maximum ratio 3:1 between slab produced in AMG and end targeted plate thickness, from 250 to 80 mm. The trials were performed in ArcelorMittal Galati in industrial conditions - Heavy Plate Mill [4] (equipped with two quarto reversing mills stand). Rolling simulation with new chemical compositions based on low alloying on Mo [5], Nb [6], Ti [7] and rolling schedule was done using SIROLL Level 2 Automation system. We checked if the process parameters targeted, namely TBT (transfer bar thickness), SRT (start rolling temperature) and FRT (final rolling temperature) below the non-recrystallization temperature T_{nr} close to critical point A_{r3} can be reached without the overall stand technical limit: force, torque, speed. The value of T_{nr} and A_{r3} is raised by the addition of micro-alloying elements: Nb and Ti. For these trials were used two slabs with 250 thicknesses and two plates were rolled, with 70 and 80 mm targeted thickness in TMR mode. The parameters monitored, that is TBT, SRT, FRT, pre-calculated in simulation, were reached in industrial rolling conditions with a delta admitted for each parameter: TBT = ± 3 mm; SRT and FRT = ± 10 °C. Total amount of deformation ≈ 58% below T_{nr} was distributed in 6 rolling passes. The speed of WR (work rolls) was constant at 2 m/s, leading to uniformity of grain size in rolling direction, despite the high targeted thickness. Plates were cooled in pile for dehydrogenation purpose. All the tests were performed in the authorized lab of AMG in order to characterize the mechanical properties [5] of material:

- Spectral analysis: to compare heat analysis on ladle with end product;
- Mechanical tests:
  - Tensile test: UTS [MPa]; Ys [MPa]; Elongation E [%];
  - Charpy-V notch test – toughness – KV values [J];
- Metallographic analysis, SEM and Optical: microstructure, substructure, segregations and inclusions.

2. Experimental setup

SIROLL rolling simulation was done and screenshot of HMI was captured in Figure 1.

SIROLL software – level 2 automation of rolling process in current use has a simulation module. the process parameters were checked: force, torque and speed supposed to be in stand limits. The metallurgical parameters checked were: SRT_Q1; TBT; SRT_Q2; FRT_Q2 supposed to be in the established theoretical domain with max ± 5% of deviation. A screenshot image with rolling simulations for a plate targeted with 55 mm in TMR is shown in Fig. 1:

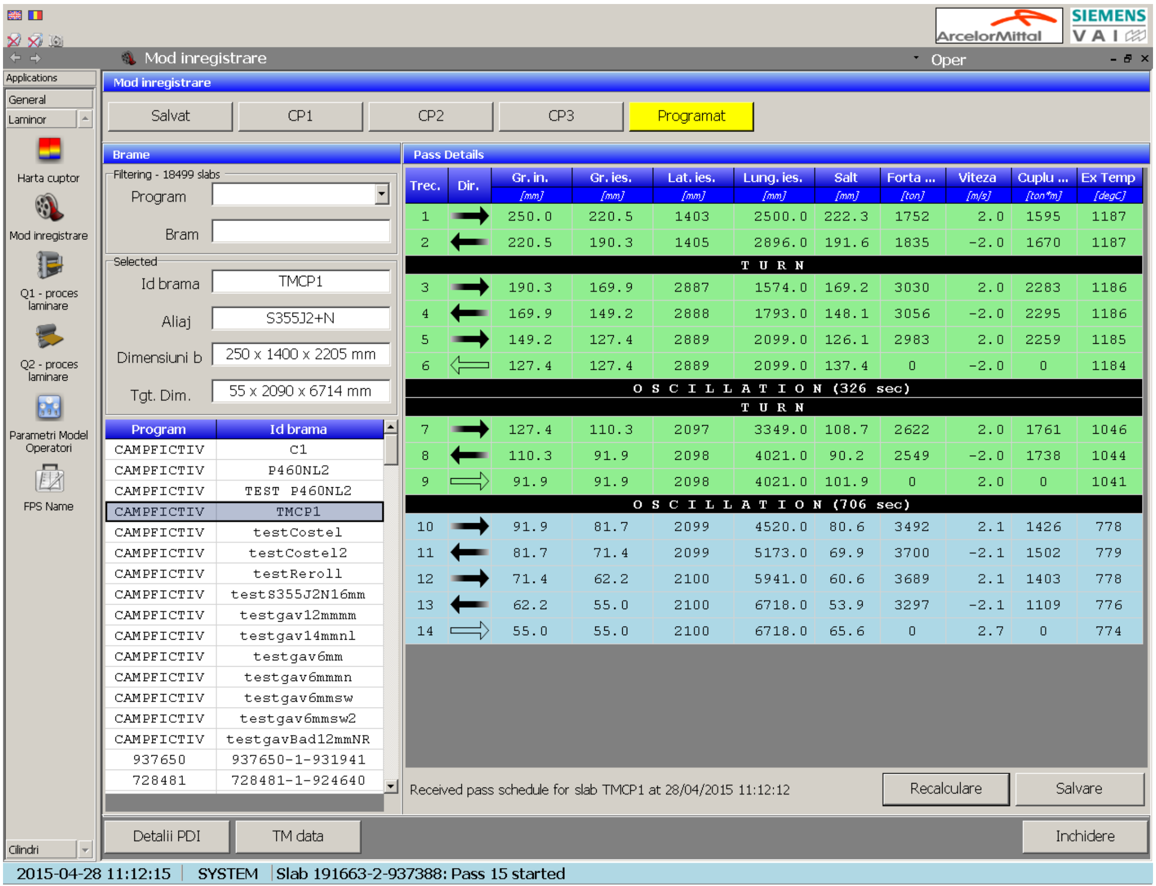

***Fig. 1.** Rolling simulation on 55 mm plate targeted - SIROLL*

2.1. Matrix chemical composition

2 slabs with M1 - chemical composition in target and realized elements (Table 1) were allocated to this industrial trial.

The improved property combination of strength and toughness was made possible by maximizing grain refinement thus substituting for the strengthening effect of carbon. In addition, modern steel making processes allow the mass production of low sulfur steels [8]. Figure 1 indicates, which improvements in ductility are achieved, especially in transverse and through thickness direction (5), by lowering the sulfur content.

Table 1. *Chemical composition in mass percentage %*

M1									
C min	C max	Mn min	Mn max	Si min	Si max	Si target	S realized	P min	P realized
0.085	0.100	1.250	1.400	0.250	0.400	0.330	0.004	0.000	0.012
N max	N target	**∑ (Ni+Cu+Cr)**	Mo min	Mo max	**∑ min (Nb+Ti+V)**	**∑ max (Nb+Ti+V)**	Ca min	Ca max	H2 realized
0.007	0.006	0.50	0.055	0.065	0.050	0.078	0.0005	0.0015	0.00026

Table 2. *Data identifications for slabs used in trial*

Traceability				**Slab dimensions [mm]**			**Mother plate target [mm]**			
Program	**Daughter slab**	**Heat no.**	**Bauman class**	**Length**	**Width**	**Thickness**	**Length**	**Width**	**Thickness**	**Qty.**
171121	1	935090	1	2620	1500	250	6000	2000	70	7.70
171122	1	935090	1	2995	1500	250	6000	2000	80	8.80

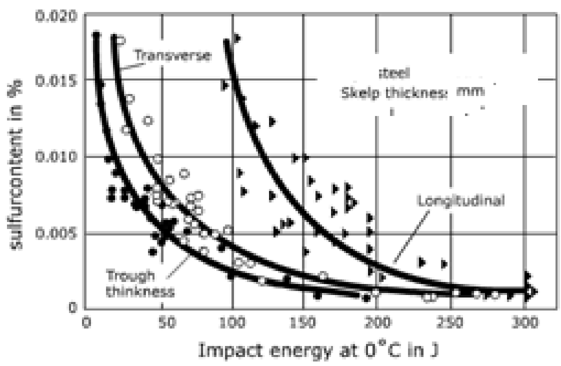

Fig. 2. *Sulphur content*

In order to obtain the required properties in thermomechanical rolling of heavy plate, a high deformation in the temperature range of non-recrystallization of austenite is to be introduced. The finish rolling temperature reaches in the metastable austenite the critical point A_{r3}.

The mechanical properties required are presented in Tables 3-5 according to the European standard for structural steel with delivery conditions in thermo-mechanical rolling state EN 10025/4 of 2009.

Afterwards, rolling process sampling was taken in order to check mechanical characteristics.

Table 3.

EN10025/4 requirements: Yield strength; Tensile strength, Elongation and carbon equivalent						
Thickness	**Steel grade**	**YS min [MPa]**	**TS min [MPA]**	**TS max [MPa]**	**E %**	**CEV [%]**
<40 mm <=63 mm	S355M S355ML	335 335	450 450	610 610	22 22	0.40 0.40
<63 mm <=80 mm	S355M S355ML	325 325	450 450	610 610	22 22	0.45 0.45

Table 4.

Minimum values of impact energy for impact tests on longitudinal V-notch tests pieces for thermomechanical rolled steel in Joules [J] at test temperature in Celsius degrees [°C]								
Thickness	Steel grade	+20	0	-10	-20	-30	-40	-50
60-80mm	S355M	55	47	43	40	-	-	-
	S355ML	63	55	51	47	40	31	27

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Table 5.

Z Test units for flat products - extract from EN10164-2004				
Quality class	Test units for S>0.005%		Test units for S<=0.005% Cast *d*	*d* Products with the same heat treatment. *e* Unless otherwise agreed at the time of the order.
	Parent plate		max 40 t	
Z15	if agreed	xe	x	
Z25	x	-	xe	
Z35	x	-	xe	

3. Thermomechanical rolling process

Our purpose is to avoid the accelerate cooling, that means the rolling schedule will target the frt close to A_{r3}. Rolling process will be divided in two phases. One phase will be in roughing area with equalizing and broadsiding sequence up to transfer bar thickness between two stands – roughing mill and finishing mill. After oscillation time to achieve SRT in finishing mill, finishing sequence will be rolled. FRT will reach the limit of Ar_3 in austenitic zone.

Trial summary:

4 slabs used; Total qty = 37 t; Thickness targeted: 60; 70 and 80 mm.
Results:
70 mm - 1 slab - 1 pass in full auto mode;
80 mm - 1 slab - 1 pass in full auto mode;
TMR = Thermomechanical rolling process;
TBT = transfer bar thickness;
SRT = start rolling temperature;
FRT = final rolling temperature.

For both plates rolled with thickness 70 and 80 mm tension tests were performed in transverse direction

Table 6. *Process parameters data*

Rolling process parameters								
Type of Rolling process	**Preset L2 AGC [°C]**	**SRT Q1 [°C]**	**Preset L2 AGC TBT [mm]**	**TBT exit thick [mm]**	**SRT preset L2 AGC [°C]**	**SRT Q2 [°C]**	**FRT preset L2 Q2 [°C]**	**FRT Q2**
Auto	1148	1147	133	130	856	853	783	778
Auto	1153	1150	133	131.2	853	839	781	776

4. Trial lab results

For toughness properties Charpy V-notch test was performed. Tests were performed at top and bottom of surface plate, the toughness guarantee being at -20ºC. For S355ML with toughness guarantee at -40ºC, the minimum limit is 325 MPa and it was accomplished.

Z trough-thickness coefficient is very good for such thicker plate of 7-80 mm, with an average value higher than Z35 condition at 38% (see Fig. 4).

Very good values for TS in middle of the targeted range, and for YS it is in sustainable average with 40 MPa, higher than the required minimum limit of 335 MPa for S355M - meaning toughness guarantee at -20 ºC. For S355ML with toughness guarantee at -40 ºC the minimum limit is 325 MPa and this was accomplished.

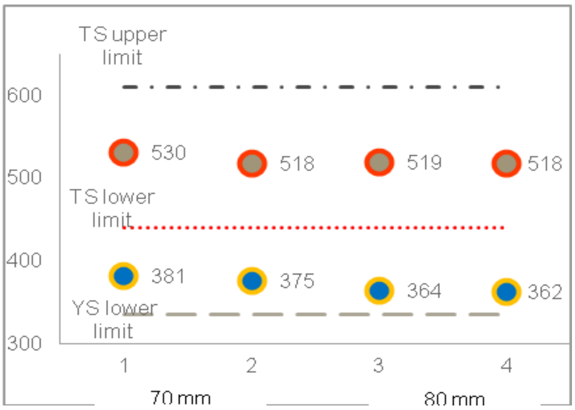

Fig. 3. *Mechanical properties TS and YS*

Z trough-thickness coefficient is very good for such thicker plate of 7-80 mm with an average value higher than Z35 condition at 38% (see Fig. 4).

Table 7. *Mechanical properties: TS and YS in [MPa] and elongation in percentage %*

Lab sample no.	Program	mother plate	heat no.	Thickness [mm]	Steel grade fit	Steel grade fit	Standard fit	TS min S355 M	TS min S355 ML	TS lab	TS max S355 M	TS max S355 ML	YS min S355 M	YS min S355 ML	YS lab MPa	E %
3317 top	171121	1	935090	70	S355M	S355ML	EN10025/4	450	440	530	610	600	335	325	381	34
3317 bottom	171121	1	935090	70	S355M	S355ML	EN10025/4	450	440	518	610	600	335	325	375	35
3316 top	171122	1	935090	80	S355M	S355ML	EN10025/4	450	440	519	610	600	335	325	364	32
3316 bottom	171122	1	935090	80	S355M	S355ML	EN10025/4	450	440	518	610	600	335	325	362	32

Table 8. *Trough-thickness Z coefficient*

Lab sample no.	Thickness [mm]	Z min [%]	Z [%]
3317	70	35	39.3
		35	38.2
		35	39.1
3316	80	35	36.9
		35	38.2
		35	38.3

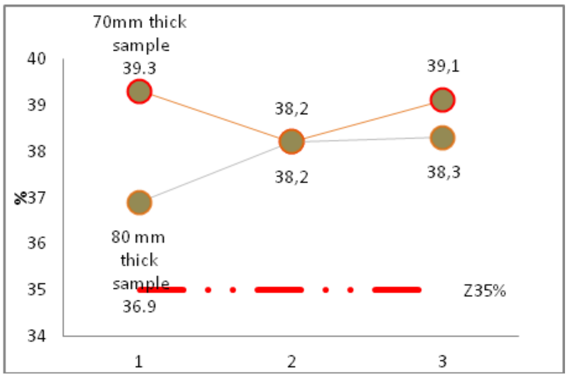

Fig. 4. *Z coefficient*

Table 9. *Charpy V-notch test at -20 ºC in longitudinal direction*

Lab sample no.	Thickness [mm]	V-notch test directions	Test Temperature [°C]	KV1	KV2	KV3	KV average	KV min S355M	KV min S355ML
3317/F1 1/4	**70**	longitudinal	-20	238	240	229	235.7	40	47
3317/F1 1/2 middle	**70**	longitudinal	-20	110	98	107	105.0	40	47
3317/F2 2 mm at bottom	**70**	longitudinal	-20	192	202	184	192.7	40	47
3316/F1 1/4	80	longitudinal	-20	210	224	218	217.3	40	47
3316/F2 1/2 middle	80	longitudinal	-20	58	59	42	53.0	40	47
3316/F2 2 mm at bottom	80	longitudinal	-20	220	219	208	215.7	40	47

Charpy V-notch tests were performed at two temperatures in order to check both steel grade S355M and S355ML do to the fact that the differences are given by the test temperatures: -20 ºC, and -40 ºC. *(see Table 9 and 10)*.

Figure 5 shows very good value for toughness also in middle thickness, in average higher than 100 J.

In Figure 6 we can observe good toughness values for 80 mm thickness on surface, meeting the standard requirement - in the middle of lower limit.

Very good toughness values [Joules] can be noticed in Fig. 7 on surface as standard requirements demand, but lower than minimum limit in average 20 Joules at -40 ºC test temperature.

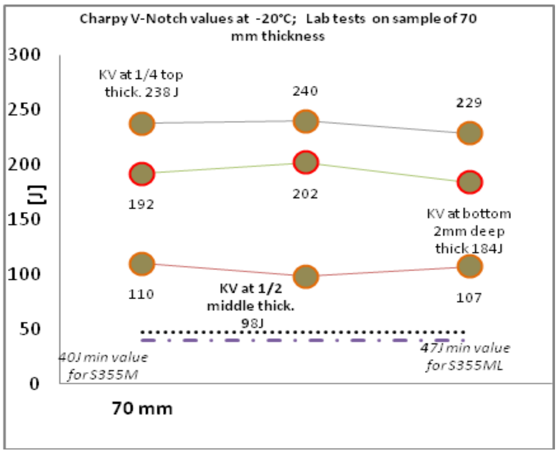

Fig. 5.

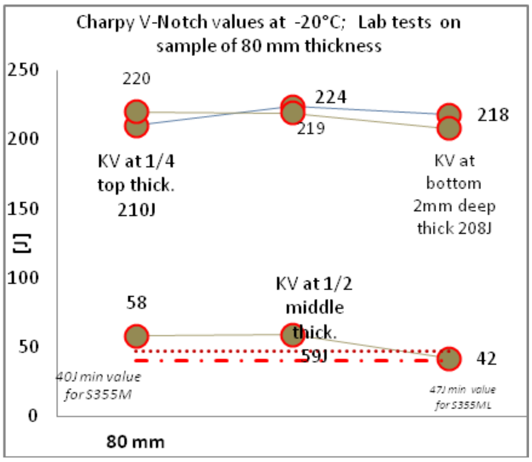

Fig. 6.

Table 10.

Lab sample no.	Thickness [mm]	V-notch test directions	Test Temperature [°C]	KV1	KV2	KV3	KV average	KV min S355ML
3317/F1 1/4	**70**	longitudinal	-40	120	116	101	112.3	31
3317/F1 1/2 middle	**70**	longitudinal	-40	68	19	20	35.7	31
3317/F2 2mm at bottom	**70**	longitudinal	-40	162	184	168	171.3	31
3316/F1 1/4	80	longitudinal	-40	170	168	28	122.0	31
3316/F2 1/2 middle	80	longitudinal	-40	8	9	8	8.3	31
3316/F2 2mm at bottom	80	longitudinal	-40	162	158	30	116.7	31

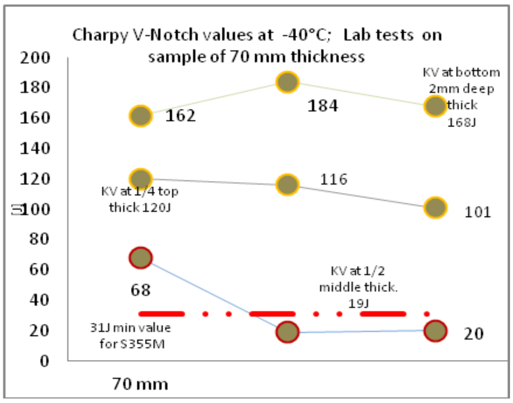

Fig. 7.

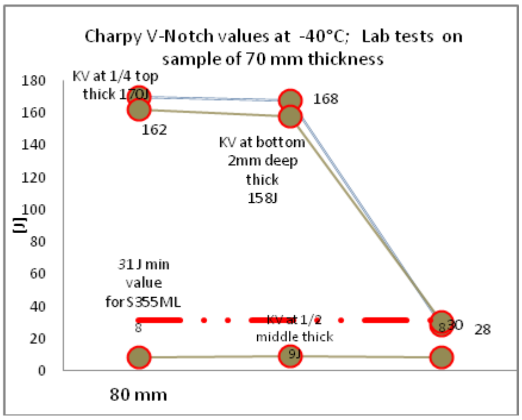

Fig. 8.

Variations on toughness values [Joules] in Fig. 8 on surface according to standard requirements, lower than the minimum limit, also in average 8 Joules at -40 ºC test temperature for 80 mm thickness.

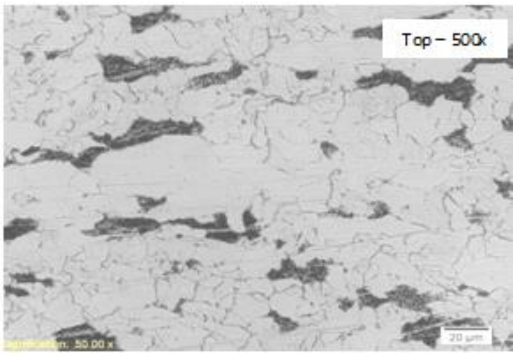

Fig. 9. *Metallographic analysis - sample no. 3317 - thick. 70 mm at surface - 2 mm deep in thickness*

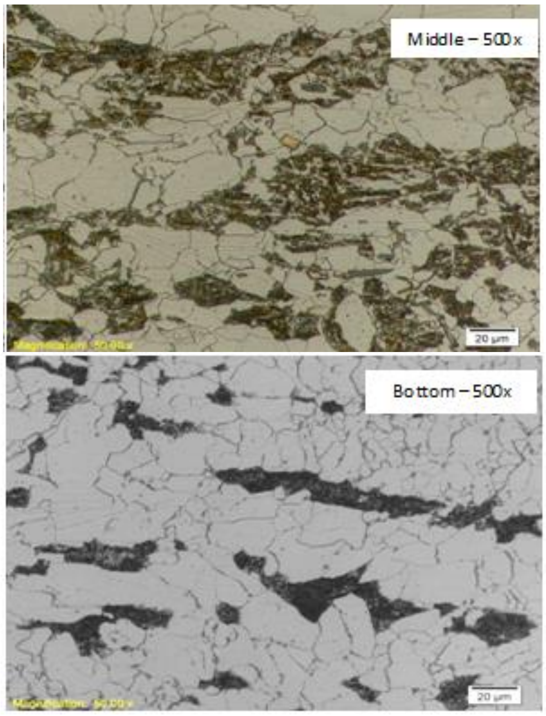

Fig. 10. *Metallographic analysis - sample no. 3317 - thick. 70 mm and SEM in middle and bottom*

Discussion on metallographies 70 mm thickness:

● Lamellar type of ferritic-pearlitic structure, partial decarburization 115 µm on the edge, accicular aspect;

● Cementite presence at the grain boundaries;

● Pearlitic structure has a different grade of dispersion;

● Lamellar type of coarse sorbite-pearlitic disbanded structure;

● Small segregations; 1. nitrides presence - orange in middle.

Grain size:

1. top - 7÷9.5 points;
2. middle - 6÷9 points;
3. bottom - 7÷9.5 points.

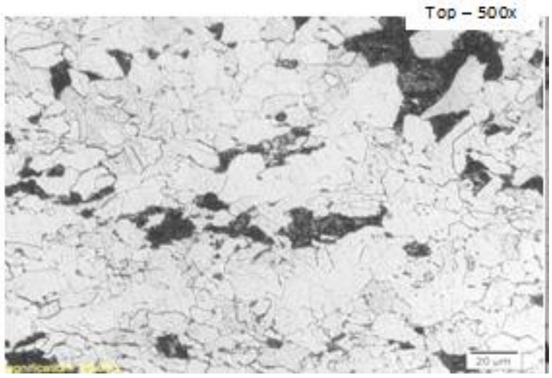

Fig. 11. *Metallographic analysis - sample no. 3316 - thick. 80 mm at surface - 2 mm deep in thickness*

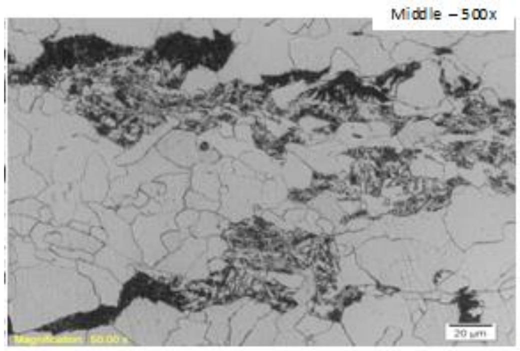

Fig. 12. *Metallographic analysis - sample no. 3316 thick. 80 mm in middle thickness*

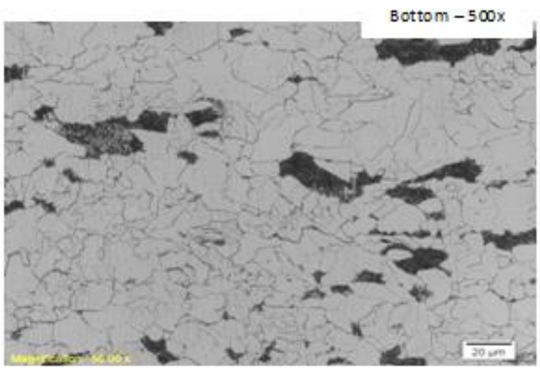

Fig. 13. *Metallographic analysis - sample no. 3316 thick. 80 mm at 2 mm deep thickness from bottom surface*

Discussion on metallographies 80 mm thickness:

● Lamellar type of ferritic-pearlitic structure, partial decarburization 270 µm on the edge, accicular aspect.

● Pearlitic structure has a different grade of dispersion.

● Lamellar type of coarse sorbite-pearlitic disbanded structure.

Grain size:

1. top - 7÷9.5 points;
2. middle - 6÷9 points;
3. bottom - 7÷9.5 points.

SWOT analysis:

Strength:

- S355M steel grade will cover the thickness range from 50.01 ÷ 80 mm.
- Thermo-mechanical rolling process – full auto mode.

Weakness:

- Time of production around 18 minute/mother plate.

Opportunities:

- Increased thickness range up to 84 mm.
- Preservation of the same chemistry.
- Added value.
- Fine tuning of rolling process.

Threats:

Occurrence of segregations in the middle of the higher thickness.

5. Conclusions

With the actual chemical compositions used in this experimental rolling we are confident about the feasibility for steel grade S355M to cover the thickness range from 50.01 up to 80 mm.

In order for the steel grade S355ML to start to increase the thickness range, in the first step the slab dimensions should be changed or different type of rolling should be used do to the lowest toughness achieved in the middle thickness.

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