Production of Steel Heavy Plates Up to 100 mm by TMCP With Accelerated Cooling at NLMK DanSteel

This paper contains investigations of microstructure and mechanical properties of industrial samples of low-carbon microalloyed steel heavy plates of S420M and S420ML quality according to EN 10025-4:2019 and used for offshore wind foundations. The chemical composition and process parameters of TM+ACC heavy plates used were developed by the authors. The technology is fully implemented at NLMK DanSteel. The authors describe the specifics of designing the chemical composition and selecting the technological parameters for the thermomechanical processing.

There has been a growing interest in the production of heavy plate products 60–100 mm in thickness from S420M and S420ML structural steel grades in compliance with EN 10025-4:2019, which can be attributed to the increasing demand for this type of product in northern and central Europe. Heavy plates over 60 mm in thickness are increasingly used in wind energy and bridge construction industries, as well as in marine structures and civil engineering. The growing demand for M/ML steels is also driven by the gradual (by thickness groups) replacement of traditionally used conventional S420N/NL steels produced by means of the normalizing process (+N)* with more advanced S420M/ML steel grades produced under thermomechanical processing schemes, including accelerated cooling schemes (thermomechanical processing with accelerated cooling, or TMCP+ACC). The growing interest of heavy plates that are being supplied or undergo thermomechanical processing is also confirmed by the introduction of a new edition of the EN 10025-4:2019 standard to replace the EN 10025-4:2004 edition, thus increasing the maximum thickness of S420M and S420ML thermomechanically rolled products from 120 to 150 mm.

The basic requirements of the EN 10025(-3 and -4):2019 standard to the yield strength, tensile strength and impact energy of the structural steel being the same, the actually used chemical composition of S420N/NL and S420M/ML steels is markedly different, with S420M/ML steels having much lower alloying content. This basically means that these steels have reduced carbon, manganese, silicon, niobium and vanadium content, which contributes to lower levels of cold crack sensitivity, increased Z-properties and better weldability of steel, regardless of whether the heat input is low (0.5–1.2 kJ/mm) or high (3.5–5.0 kJ/mm). Lower alloying content also contributes to the reduction of the cost by EUR13–25/ton depending on the thickness and low temperature toughness group of heavy plates. On the other hand, normalized S420N/NL plates are traditionally considered to be more reliable due to the simplicity of the manufacturing process and, therefore, to the minimized fluctuations of technological parameters during heavy plate production, which is an important criterion of reliability and is often specified in technical regulations and design documentation.

From the standpoint of physics of the normalization procedure (+N),

* +N stands for “hot rolling of heavy plates with subsequent furnace normalizing heat treatment.”

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the major goal is to provide an optimal thermal cycle for the heating of the heavy plate above the $\alpha\rightarrow\gamma$ transformation ending range (the Ac₃ point) and subsequently to cool the heavy plate in still air to obtain a dispersed ferrite-pearlite through-thickness microstructure. Where S420M/ML steels are produced using the TMCP+ACC technology, the number of technological parameters affecting the microstructural condition and, consequently, the range of mechanical properties is significantly increased, thus contributing to the multi-factor character of the manufacturing process. As the final thickness of plates and slabs increases, the correlation between the chemical composition, technological process parameters, microstructural condition, and the range of mechanical properties of steel heavy plate becomes stronger and generally more difficult to define. This should be taken into account when developing the target chemical composition and defining the range of technological process parameters. On the other hand, the production of heavy plates using TMCP+ACC creates additional opportunities for the generation of different combinations of mechanical characteristics (in terms of level and ratio) preserving the same chemical composition. Due to this flexibility, the TMCP+ACC process has an advantage over the +N process, which may be useful in the production of heavy plates with the unique combinations of the chemical composition and mechanical properties which are in demand on the market.

This article aims to describe the specifics of the chemical composition, manufacturing process, microstructural condition and mechanical properties of pilot batches of heavy plates up to 100 mm in thickness made of the S420M/ML structural steel produced by thermomechanical processing with accelerated cooling at the NLMK DanSteel Mill Quarto 4200.

### Discussion

**Standard and Project Requirements** — It seems advisable to split the requirements to the EN 10025-4:2019 S420M/ML structural steel into three complexity classes. The first and simplest class shall include the EN 10025 basic requirements to the chemical composition and basic mechanical properties. The second class shall include customer requirements for lower content of chemical elements in steel. Most sought-after restrictions are restrictions to the maximum permissible content of carbon (e.g., not more than 0.06%), manganese (not more than 1.40%), silicon (not more than 0.25%) and niobium and vanadium (not more than 0.030% in total). The carbon equivalents (CEQ) $\leq$ 0.34% and Pcm $\leq$ 0.16% may be restricted additionally.

The third class includes project requirements with additional restrictions to the chemical composition and mechanical properties of the base metal and/or welded joint. The regulatory requirements to the S420ML heavy plates and additional cumulative project requirements in offshore wind power and bridge construction industries are shown as an example in Tables 1 and 2. It should be noted that project requirements are individual and vary depending on the purpose, economics, specifics of the steel structure manufacturing process, its elements, etc.

### Table 1

<table>
<thead>
<tr>
<th>Requirements</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Nb</th>
<th>V</th>
<th>Ti</th>
<th>Mo</th>
<th>CEQ</th>
<th>Pcm</th>
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<tr>
<td>EN 10025-4¹</td>
<td>0.16</td>
<td>1.70</td>
<td>0.50</td>
<td>0.050</td>
<td>0.12</td>
<td>0.05</td>
<td>0.20</td>
<td>0.47</td>
<td>—</td>
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<tr>
<td>Additional project requirements²</td>
<td>0.06</td>
<td>1.40</td>
<td>0.25</td>
<td>0.030</td>
<td>0.030</td>
<td>0.020</td>
<td>0.01</td>
<td>0.34</td>
<td>0.16</td>
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</tbody>
</table>

¹Cr max 0.30%; Ni max 0.80%; Cu max 0.55%; N max 0.025%
²Requirements to the Cr, Ni, Cu, N min/max content are variable

### Table 2

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Unit</th>
<th>EN 10025-4 64–80 mm</th>
<th>Additional project requirements 61-100 mm</th>
<th>64–80 mm</th>
<th>81–100 mm</th>
<th>64–80 mm</th>
<th>81–100 mm</th>
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<tr>
<td>Yield strength, $R_{H}$</td>
<td>MPa</td>
<td>$\geq$380</td>
<td>$\geq$370</td>
<td>$\geq$420</td>
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<tr>
<td>Tensile strength, $R_{m}$</td>
<td>MPa</td>
<td>480–640</td>
<td>470–630</td>
<td>520–640</td>
<td>520–630</td>
<td></td>
<td></td>
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<tr>
<td>Percentage elongation, $\Delta$A₂₀₀</td>
<td>%</td>
<td>$\geq$19</td>
<td>$\geq$22</td>
<td>$\leq$0.89</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$R_{H}/R_{m}$ ratio</td>
<td>—</td>
<td>—</td>
<td>$\leq$0.89</td>
<td>—</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impact energy in L direction</td>
<td>J</td>
<td>47/31/27/—</td>
<td>100/100/100/80</td>
<td>100/100/100/80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impact energy in T direction</td>
<td>J</td>
<td>27/20/16/—</td>
<td>100/100/100/80</td>
<td>100/100/100/80</td>
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<tr>
<td>Impact energy in L direction</td>
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<tr>
<td>Impact energy in T direction</td>
<td>J</td>
<td>—</td>
<td>80/80/80/60</td>
<td>80/80/80/60</td>
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Examples of Applications — There are many different common and special applications in which heavy plate products 60–100 mm in thickness from S420M and S420ML structural steel grades are used (or could be used). The most advanced applications are related to structural offshore and bridge-building segments. For example, transition pieces (Fig. 1a) of monopiles, which at present are the most advanced type of foundation for the construction of offshore wind turbines, are commonly manufactured from 50- to 100-mm-thick heavy plates. Transition pieces are needed in order to connect the towers of the offshore wind turbines with the respective monopile. Made of steel pipe construction, the primary steel part, as well as secondary steel elements like platforms, ladders or boat landing systems, transition pieces are essential construction components of offshore wind turbines. Components of offshore construction elements such as high-load spreader bars, pile followers, crane pedestals (Fig. 1c), spud poles, thick-walled tubular sections and dead weight support caissons (Fig. 1d) are also produced from thick heavy plate products. Even for more traditional offshore structures like jack-ups and rigs, a change to higher-strength grades can be advantageous due to lower weight and better weldability of these grades. Examples of special application could be centric and eccentric cones (Fig. 1b) with various aperture angles and special edge processing, such as crimped edges, which are used to strengthen construction, including ice protection function.

Main Equipment — When heavy plates 60–100 mm in thickness are produced by means of the TMCP+ACC technology at NLMK DanSteel, Mill Quarto 4200 is used, which includes the following
basic equipment: a continuous multi-zone reheating furnace (Fig. 2a), a 4-high reversible stand (Fig. 2b), an accelerated cooling unit (Fig. 2c) and a hot plate leveler (Fig. 2d).

The continuous walking beam reheating furnace has six zones and a capacity of up to 120 tons/hour. It runs on natural gas with a heating value of up to 40 MJ, the maximum specific consumption of heat for slab heating being 38 m³/ton. Slabs are moved in the furnace in three independent rows. The first and the third row are used to reheat slabs 200–250 mm in thickness and the middle row is used to reheat the slabs 310–400 mm in thickness (Fig. 2a), which makes it possible to control the heating time depending on the thickness and slab chemistry. The target slab discharging temperature and the required heating time are ensured by means of an automated control system and a mathematical metal heating model.

The 4-high stand with a 4.550-mm-long working roll body makes it possible to implement intensive TMCP modes to obtain heavy plates with a given set of mechanical properties and high-precision geometry to meet the requirements of EN 10029 and similar tolerance standards. The stand is equipped with a roll shifting system (CVC plus), a roll bending control system (WRB) and a hydraulic roll gap control (HGC). These systems in combination with the self-adapting mathematical modeling of heating and rolling processes ensure a stable flow of metal in the deformation zone when slabs up to 400 mm in thickness are rolled in the first passes in intensive deformation modes.

The 24-m-long accelerated cooling unit (AC) makes it possible to implement intensive water/air cooling modes for heavy plate processing, including multi-stage processing. The AC is equipped with 18,240 nozzles, 45 independent control and adjustment sections, end and side-edge masking systems, an oscillation option, and operates in five different modes: (1) Interstage cooling; (2) Accelerated cooling; (3) Direct quenching; (4) Soft cooling; and (5) Multi-stage final cooling.

The design of the 9-roller hot plate leveler enables the automated leveling of the TMCP heavy plates up to 120 mm in thickness in the temperature range of 350–850°C. The maximum leveling speed is 2.5 m/second. The HPL is equipped with tilted crossbars with independent adjusting screws. The maximum leveling force is 29 MN.

Due to the fact that the TMCP+ACC process has a large number of adjustable and controllable technological parameters, the main line of the NLMK DanSteel Mill Quarto 4200 operates in automatic mode and is equipped with 16 pyrometers, three thermal scanners, and more than 50 sensors that track metal position and movement in the flow of the main line of the rolling mill. The data received from these devices are combined into manufacturing database packages at the L2 automation level and are used to self-adapt the control models of the continuous furnace, the rolling stand and the accelerated cooling unit.

Chemical Composition Design — When developing the chemical composition of heavy plates 60–100 mm in thickness with the minimum yield strength of 370–420 MPa (see Table 2), NLMK DanSteel uses low-alloy steels with a given carbon and manganese content to obtain the target level of strength. Low carbon content (not more than 0.07%) as well as the low value of CEQ (not more than 0.35%) are necessary to form the target microstructural condition and ensure a high level of low-temperature impact toughness of the base metal and the heat-affected zone of the welded joint. The silicon content of steel in the range of 0.15–0.25% raises the possibility of using heavy plates in process chains with subsequent galvanization and decreases the intensity of metal flow (the appearance of dross) during scarfing and cutting. Similarly, the aluminum content has an optimum range of 0.03–0.04%, above which the risk of formation of aluminate inclusions increases. It is advisable to use steel with reduced content of harmful impurities and gases (S ≤0.002%; P ≤0.010 %; H ≤2 cm³/100 g).

In order to obtain M-grade rolled products (with impact tests down to −20°C), additional alloying of steel is not strictly necessary, but for an overall increase in ductility and to reduce the temperature of the ductile-to-brittle transition for ML-grade manufacturing (with impact tests down to −50°C) it is appropriate to add nickel and, in some cases, chromium in the maximum total amount of 0.50%. For TMCP, traditional microaddition of niobium up to 0.030% contributes to the efficient refinement of microstructural elements.

Manufacturing Process — Continuously cast (CC) slabs with thickness up to 355 mm from vacuum degassed (VD) converter steel produced at Novolipetsk Iron and Steel Works (NLMK) are used for the production of the S420M/ML heavy plates up to 100 mm in thickness at the NLMK DanSteel. In order to improve the macrostructural quality of slabs of each size, the Iron and Steel Works specialists have developed individual modes of dynamic soft reduction, which make it possible to increase the level of low-temperature impact energy, including in 1/4 and 1/2 thickness of rolled products. Controlled slow cooling of slabs is used for more efficient removal of residual atomic hydrogen and partial relaxation of residual internal stress.

CC slabs are rolled at the NLMK DanSteel Mill Quarto 4200. Slabs are heated in a 6-zone continuous slab reheating furnace with walking beams. The heating duration is 5–8 hours depending on slab thickness. The slab setup temperature varies from 1,130
to 1,180°C, making it possible to regulate the degree of solubility of carbonitride forming elements determining the required grain size. The first TMCP stage is performed at temperatures ≥980°C. In order to obtain a given level of yield strength and impact energy at target temperatures in longitudinal and transverse directions and to ensure an increased through thickness uniformity of mechanical properties, the plates, depending on their thickness, are rolled in γ and (γ+α) regions in intensive two- or three-stage thermomechanical rolling modes with intermediate and final accelerated cooling. In two-stage rolling, the ratio of the thickness of semi-finished rolled products to the final thickness of the plate depends on the final thickness of rolled products and is ≈1.6–3.0. In three-stage rolling, the ratio of rolled products thickness before the second and the third stage is ≈2.5–3.0 and ≈1.5–2.0, respectively. The interstage cooling of semi-finished rolled products is performed in still air or by means of interstage accelerated cooling (IC) at a rate of 0.3–1.2°C/second. The final accelerated cooling of rolled products starts from the lower part of the γ region or from the upper part of the (γ+α) region and is completed in one or several stages to ensure an optimal balance between the ACC intensity and the flatness of rolled products. As the thicknesses of rolled products is high, the cooling rates are close to the maximum of AC possibilities. It is noteworthy that there is a need for significant supercooling of subsurface (1/8 t) layers of rolled products of up to 150–200°C. The reduced CEQ reduces the negative impact of this surface supercooling.

Specific Aspects of the TMCP+ACC Process — The issue of metallurgical quality of rolled products 60–100 mm in thickness manufactured by means of the TMCP+ACC procedure has a “volumetric” nature, suggesting that there is a need to take into account the impact of hot plastic deformation conditions, intermediate and final accelerated cooling parameters on the formation of microstructure and type of crack formation mechanism under static and dynamic loading across metal thickness. For example, it is known that the pattern and starting temperature of γ→α transformation depends on the microstructural condition of hot-deformed austenite. In turn, the condition of austenite, i.e., the grain size and the number of defects and imperfections of the lattice, depends on the degree7–9 and temperature10,11 of deformation. The lower the degree and the temperature of deformation, the more limited the possibilities for recrystallization,12 the bigger the grain size, and the higher the thermodynamic stability of austenite, and hence the lower the Aγ point. When the end of hot deformation passes into the (γ+α) region, and especially when deformation passes are taking place already below the Aγ point, ferrite is subjected to hardening, which results in increased steel strength as well as reduced ductility, and impact energy as a hard-deformed ferrite substructure is created. The degree of through-thickness ferrite hard working and thus the steel properties will depend, among other things, on the degree of deformation penetration into the thickness of semi-finished rolled products, with minimum values attained in the mid-thickness of semi-finished rolled products and maximum values in layers close to the surface. Any subsequent AC use further increases the temperature difference and has a direct impact on the qualitative and quantitative characteristics of the final microstructure of heavy plates.

These patterns confirm that when studying the influence of the TMCP+ACC modes on the microstructure and properties of heavy rolled products, the correlation between the components “chemical composition – process parameters – microstructure – mechanical properties” should be considered not for rolled products in general, but for several layers, that should be roughly separated depending on the temperature, deformation and cooling parameters of the TMCP+ACC process.

It should be noted that when selecting the temperature and deformation modes of TMCP+ACC, the key objective is to ensure the maximum possible formation of a homogeneous microstructure with a gradual (physically natural) enlargement of the average grain size and/or structural elements of the matrix from the surface toward the center of heavy plate. When developing the temperature and deformation modes of TMCP+ACC for rolled products with high final thickness, specifically for rolled products over 80 mm in thickness, in the temperature range of 740–820°C, it is important to take into account not only the competing thermal effects of deformation heating and natural cooling of the metal during rolling, but also their different through thickness degrees in rolled products during deformation and in interdeformation pauses.

As an example, Fig. 3 shows the graphs of the per-pass temperature difference between 1/8 and 1/2 of thickness of heavy plate with a final thickness of 60, 70, 90 and 100 mm at the finishing deformation stage where the rolling end temperature is 800, 780, 760 or 740°C. The width and the length of rolled products of all thicknesses are 3,000 x 12,000 mm. In all cases, the temperature difference of the second pass tends to increase, which can be attributed to the working conditions of the rolling stand and the measuring equipment. As it can be seen in Fig. 3a, in production of heavy plates of 60 mm thickness with the temperature at the end of the finishing stage of rolling (Tend roll.) setup 740°C, the temperature difference between 1/8 and 1/2 of thickness is close to 40°C. As Tend roll. increases to 800°C, the temperature difference grows to 55°C. The analysis of results
in Fig. 3d shows that at $T_{end \text{ roll}} = 740^\circ$C, the difference in 100-mm plates increases to ~70°C, and when $T_{end \text{ roll}}$ grows to 800°C, the difference approaches 100°C, with its maximum at 105°C during pass 2. The patterns shown in Fig. 3 have a significant impact on microstructural condition before accelerated cooling, which will subsequently affect the level of mechanical properties of steel.

As an example, Fig. 4 shows a graph of temperature differences in the direction of thickness of heavy plate with the final thickness of 100 mm during single-stage accelerated cooling. Average calorimetric values were used as the setup parameters of the accelerated cooling process: $T_{AC \text{ beginning}} = 770^\circ$C, $R_{AC} = 5^\circ$C/second, $T_{AC \text{ end}} = 580^\circ$C. Among the results, it is necessary to note a significant increase in temperature differences during ACC close to maximal values ~600°C, when rolled products leave the accelerated cooling unit. Further heating of surface layers with the heat from central layers smoothly evens out the temperature of rolled products within ~2.0–2.5 minutes. It should be noted that the curves shown in Fig. 4 have a certain statistical confidence interval of values. In order to improve the accuracy of results, NLMK DanSteel is working to adapt the model and take into account the influence of additional external technological and natural factors.
Microstructural Condition — It is more difficult to determine the correlation between the chemical composition, technological process parameters, microstructural condition and the range of mechanical properties for heavy plates made of low-carbon microalloyed steel over 60 mm in thickness. The major reason is the difference in temperature and degree of through-thickness cumulative deformation, which is important for the formation of the final microstructure and mechanical properties. As shown in Figs. 3 and 4, the choice of optimal technological parameters of TMCP+ACC is extremely important and, when combined with correct steel alloying/microalloying, increases the possibility of obtaining the final microstructure condition with uniform qualitative and quantitative indicators.

Separate works will be dedicated to the selection of optimal technological parameters for different chemical compositions, but the overall goal is to expand the intervals of phase/structural transformations by means of target alloying and ensuring that the potentially maximum heavy plate “volume” gets into these temperature intervals taking into account a certain difference observed during deformation and accelerated cooling. As an example, Fig. 5 illustrates the microstructural conditions of S420ML heavy plate 100 mm in thickness after the application of three TMCP+ACC modes. Steel with CEQ 0.34% was used.

TMCP+ACC mode No. 1 was implemented with end rolling temperature (T_{end roll}) close to the starting point of $\gamma \rightarrow \alpha$ transformation ($A_r^\gamma$). Consequently, the temperature interval of the AC onset was below $A_r^\gamma$. The ACC end temperature ($T_{AC\_end}$) was in the range of 600–580°C.

Due to the mentioned technological parameters of TMCP+ACC, the microstructure of $1/8$ and $7/8$ thickness of plate (Figs. 5.1.1 and 5.1.5) is characterized by the presence of a large number of large deformed ferrite grains and high-irregularity bainitic packages. The target microstructural condition, which is a homogeneous mixture of ferrite and bainite, was obtained in $1/4$ thickness (Fig. 5.1.2). The $1/2$ and $3/4$ thickness microstructure (Figs. 5.1.3 and 5.1.4) is a mixture of ferrite and pearlite which is indicative of an insufficient cooling rate.
in correct temperature region (for the given chemical composition) and its asymmetry as against the top and the bottom surfaces of heavy plate.

TMCP+ACC mode No. 2 was implemented with end rolling temperature ($T_{\text{end,roll}}$) below the starting point of $\gamma \rightarrow \alpha$ transformation $A_{\gamma \alpha}$. The ACC end temperature was also in the range of 600–580°C. The results of analysis of the microstructural condition allow for the conclusion that $1/8$ thickness of plate (Figs. 5.2.1) is characterized by a hard-worked ferrite-pearlite microstructure. The target microstructural condition, which is a highly homogeneous mixture of ferrite and bainite, was obtained in $1/4$ and $3/4$ thickness (Figs. 5.2.2 and 5.2.4). The bottom surface (Fig. 5.2.5) is characterized by an increase in the number of large deformed ferrite grains and bainitic packets and is equivalent to the microstructure of Fig. 5.1.1 in terms of quality and quantity. The $1/2$ thickness microstructure (Fig. 5.2.3) is a mixture of ferrite and pearlite, which is also indicative of an insufficient cooling rate for the given chemical composition in correct temperature region.

TMCP+ACC mode No. 3 was implemented with end rolling temperature above the starting point of $\gamma \rightarrow \alpha$ transformation $A_{\gamma \alpha}$ by 15–20°C. The ACC of plate also started before $\gamma \rightarrow \alpha$ transformation. The ACC intensity was increased and the oscillation (reverse motion) of plate inside the AC was added. The ACC end temperature was in the range of 540–520°C. The results of analysis of the microstructural condition allow for the conclusion that $1/8$, $1/4$ and $7/8$ thickness (Fig. 5.3.1, 5.3.2 and 5.3.5) have a fine dispersion target mixture of ferrite and bainite. It was found that $1/2$ and $3/4$ thickness have an increased share of ferrite component and a small amount of pearlite that was released mainly at the triple point boundaries between ferrite grains. It should be concluded that among the analyzed examples, the best result in terms of qualitative and quantitative parameters of the microstructure was obtained in TMCP+ACC mode No. 3.

Mechanical Properties Level – The strength level (Table 3) of the studied S420ML steel 100 mm in thickness measured on round-section samples taken from $1/4$ thickness of heavy plates in accordance with the EN 10025-1:2019 requirements meets the requirements as specified in Table 2. Results provided in Table 3 allow for the conclusion that the three studied TMCP+ACC modes have shown roughly the same results. This is quite explicable considering the fact that the microstructure of all the three studied heavy plates in $1/4$ thickness (where the tests were conducted) was identical (Figs. 5.1.2, 5.2.2 and 5.3.2) and had the form of a dispersed mixture of ferrite and bainite. However, despite the fact that the results of the acceptance (in $1/4$ thickness) tests were the same, the mechanical properties of plate layers in different thickness will be heterogeneous, which is primarily due to the different microstructural condition of plate produced under different temperature and cooling modes of TMCP+ACC.

In order to determine the level of strength properties in different thickness layers of the studied plates under TMCP+ACC modes No. 1 and No. 3, additional investigation tests were carried out on round-section samples in accordance with the sampling plan in Fig. 6. The axis of the first and the last samples in the set is 10 mm away from the top and the bottom surfaces. Due to the step-by-step arrangement, the through-thickness testing interval is 5 mm.

Despite the fact that the results of the acceptance (in $1/4$ thickness) tests (Table 3) were the same, the mechanical properties of layers of diverse thickness were heterogeneous in heavy plates produced under TMCP+ACC modes No. 1 (plate No. 1) and No. 3.

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**Table 3**

<table>
<thead>
<tr>
<th>TMCP+ACC mode</th>
<th>Yield strength ($R_{p0.2}$), MPa</th>
<th>Tensile strength ($R_m$), MPa</th>
<th>Percentage elongation ($A_{200}$), %</th>
<th>$R_{p0.2}/R_m$ ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 1</td>
<td>447</td>
<td>530</td>
<td>29.5</td>
<td>0.84</td>
</tr>
<tr>
<td>No. 2</td>
<td>441</td>
<td>528</td>
<td>27.0</td>
<td>0.84</td>
</tr>
<tr>
<td>No. 3</td>
<td>445</td>
<td>535</td>
<td>26.5</td>
<td>0.83</td>
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</table>

**Figure 6**

Sampling procedure for heavy plates 100 mm in thickness for investigation of tensile properties in different thickness layers.
(plate No. 3), which is primarily due to the different through-thickness microstructural conditions of steel (Fig. 5).

The top layer (up to 25 mm) of plate No. 1 is characterized by $R_{eH}$ values of 436–442 MPa and $R_m$ from 517 to 540 MPa (Fig. 7a). Further, from 26 mm to 50 mm of thickness, there is a significant reduction in $R_{eH}$ to the minimum registered value of 345 MPa and $R_m$ to 438 MPa. In the bottom thickness area from 76 to 100 mm, the $R_{eH}$ and $R_m$ levels increase to reach 385–401 MPa and 470 – 497 MPa, respectively. The differences in $R_{eH}$ and $R_m$ fully reflect the patterns of changes in the microstructural condition of the studied heavy plates shown in Figs. 5.1.1–5.1.5. The arithmetic mean of $R_{eH}$ of heavy plate No. 1 is 386 MPa, and the $R_m$ is 479 MPa.

The main difference in the results of strength investigation for plates produced under TMCP+ACC mode No. 3 (plate No. 3) is the level of $R_{eH}$ and $R_m$ in the mid-thickness layers. At a thickness range from 26 to 50 mm, $R_{eH}$ remains no lower than 390 MPa and $R_m$ no lower than 480 MPa. The average $R_{eH}$ value of plate No. 3 is 413 MPa, with $R_m$ of 503 MPa. This level corresponds to the microstructural condition described in Figs. 5.3.1–5.3.5.

Acceptance tests of longitudinal impact energy in 1/4 of thickness of plate No. 1 showed the following results: $KVL_{av}^{-20}$ 323 J, $KVL_{av}^{-40}$ 105 J and $KVL_{av}^{-50}$ 54 J. Impact energy of plate No. 3: $KVL_{av}^{-20}$ 322 J, $KVL_{av}^{-40}$ 235 J and $KVL_{av}^{-50}$ 114 J. The difference in the level of impact energy between plate No. 1 and No. 3 is also significant, as it largely depends on the microstructure of the tested layer. The result of the investigation of impact test results will be provided in future publications. No significant differences were found in Z-test results of plate No. 1 and No. 3. In both cases the reduction of area $\psi_z$ did not go below 45%.

Conclusions

The chemical composition, rolling and cooling process parameters for production of 100-mm heavy plates from low-carbon microalloyed structural steel grades S420M and S420ML were developed at the NLMK DanSteel Mill Quarto 4200 by using TMCP+ACC processing. The application of thermomechanical processing method combined with accelerated cooling ensured for steel heavy plates with CEQ 0.34% and Pcm 0.15% the required level of mechanical properties with the following average parameters: $R_m = 503$ MPa, $R_{eH} = 413$ MPa, $E_l = 27\%$, $KVL_{av}^{-20} = 322$ Joules, $KVL_{av}^{-40} = 235$ Joules, $KVL_{av}^{-50} = 114$ Joules.

The results of investigations and mechanical testing were used for extension of allowed production range heavy plate grades S420M and S420ML in thicknesses from the maximum 60 mm to the maximum 100 mm

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**Figure 7**

Level of through-thickness strength properties of the studied steel 100 mm in thickness rolled under the following modes: TMCP+ACC No. 1 (a) and TMCP+ACC No. 3 (b).

References


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