F460 Heavy Steel Plates for Offshore Structure and Shipbuilding 
Produced by Thermomechanical Control Process

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Key parameters for controlled rolling and accelerated cooling process have been determined to industrially produce 45–50 mm heavy plates of microalloyed low carbon-equivalent SiMnCrNiCu steel for offshore structures and shipbuilding. The plates were hot rolled from continuously cast slabs with a four-high 5000 mm width mill and cooled with an accelerated-cooling system. The process was characterized by heavy finish rolling reduction ratio over 63% in austenite non-recrystallization region and interrupted accelerated cooling at 460°C to form quasipolygonal ferrite and acicular ferrite as majorities of microstructure. Yield-strength greater than 460 MPa was achieved at room temperature, and Charpy V notch impact energies of 150 to ~300 J were secured even at −80°C. Coarse granular bainite and/or degenerate upper bainite were identified harmful, causing cleavage fracture. The correlation between the fraction of high-angle grain boundaries (≥15 deg) and ductile-brittle transition temperature was derived quantitatively for the advanced heavy plates. The effect of heat input during heavy plate welding on the microstructure and mechanical properties in the coarse-grained heat affect zone was discussed.

KEY WORDS: low carbon-equivalent steel; thermomechanical control process; advanced heavy plates; shipbuilding.

1. Introduction

Significant industrial progress has been made in thermomechanical processing of plate steels since 1980’s.1–6) Conventional TMCP, i.e., the combination of controlled rolling and accelerated cooling was employed to enhance microstructure-refinement. The installations of advanced accelerated-cooling (AcC) equipment with precise control of the start- and end-cooling temperatures and cooling rate provided means to produce advanced high plate steels with lean steel composition to maximize the weldability.7) The novel combination of accelerated-cooling and on-line heat-treatment process was used to pave the ways to produce dual- or multiple-phase microstructures to enhance the toughness in high-strength advanced steels.3,6) The transformed microstructure can now be modified from ferrite-pearlite to range of complex low-temperature microstructures (i.e., acicular ferrite, bainite, austenite-martensite constituents, and the multiple-phase microstructures) by means of the accelerated cooling technology in advanced high-strength high-toughness plate steels.3,6) The fine grained microstructures including quasipolygonal ferrite (QPF), homogenous acicular ferrite (AF), lower bainite (LB) and lath martensite (LM) with small effective grain size are preferred to achieve good combination of high strength and low temperature toughness. Coarse granular bainite (GB), degenerate upper bainite (DUB) in association with coarse martensite-austenite (MA) constituents give larger effective grain size, deteriorating the low temperature CVN impact performance. The studies were, however, restricted to laboratory and specific in-house scale process conditions.

Advanced heavy steel plates with room temperature yield-strength (YS) of 420 MPa and above for offshore structures and ship in frigid sea area are required to secure high strength and superior low temperature toughness. These plates are developed world wide to meet the market demand.7,11–17) The heavy plates with YS greater than 460 MPa and ductile fracture behaviour during Charpy V notch (CVN) impact tests at −40°C are of major developments.13–17) Few steel producers have developed advanced steel plates with required CVN property at −60°C.7,12) Recently, plates in conformity with Det Norske Veritas NV–F460 specifications, i.e., a minimum yield strength of 460 MPa, and secured minimum CVN impact energy of 31 J at temperatures down to −60°C, have been developed using TMCP with lean steel composition and low carbon equivalent to achieve maximized weldability.18,19) In view of limited
availability of relevant information, however, further investigation is necessary to correlate the process parameters of industrial operation to microstructure-mechanical properties relationship for optimizing the productivity and quality stability of the plate products with thickness ($t$) of $\sim 50$ mm.

The production of NV-F460 class ultra high strength heavy-thickness (45–50 mm) steel plates via TMCP route with lean steel composition is challenging when the maximum continuously cast slab thickness and mill configuration are limited. Key parameters for specific TMCP are dependent upon steel composition to achieve desired microstructures consisted of QPF, AF, GB, DUB and MA, and target mechanical properties. Integrated consideration and detailed database are necessary to bridge the considerable gap between laboratory observations and industrial process. However, such information is not adequate for the advanced heavy steel plates with the thickness of $\sim 50$ mm. In the present work, therefore, a series of full scale industrial production trials was conducted to quantify the correlation of TMCP processing, microstructures and mechanical properties in the NV-F460 class shipbuilding plates. $50$ mm thick plates with room temperature yield-strength greater than $460$ MPa, and assured low temperature CVN toughness of $\sim 300$ J even at $-80^\circ$C were produced providing a new area for the technology. The microstructural factors were characterized and quantitatively correlated with the ductile-brittle transition temperature in the industrially produced steel plates.

2. Experimental

The chemical composition of the continuously cast (CC) slabs used for industrial rolling trials is shown in Table 1. Carbon equivalent of 0.38 and $P_{cm}$ value of approx. 0.17 were chosen to maximize the weldability. Slabs of $320$ mm thickness were produced by an integrated system consisted of basic oxygen furnace, ladle furnace, RH degassing unit and vertical-bending slab caster. Measures were taken to achieve sufficient steel cleanliness to meet the demanding availability of relevant information, however, further investigation is necessary to correlate the process parameters of industrial operation to microstructure-mechanical properties relationship for optimizing the productivity and quality stability of the plate products with thickness ($t$) of $\sim 50$ mm.

The production of NV-F460 class ultra high strength heavy-thickness (45–50 mm) steel plates via TMCP route with lean steel composition is challenging when the maximum continuously cast slab thickness and mill configuration are limited. Key parameters for specific TMCP are dependent upon steel composition to achieve desired microstructures consisted of QPF, AF, GB, DUB and MA, and target mechanical properties. Integrated consideration and detailed database are necessary to bridge the considerable gap between laboratory observations and industrial process. However, such information is not adequate for the advanced heavy steel plates with the thickness of $\sim 50$ mm. In the present work, therefore, a series of full scale industrial production trials was conducted to quantify the correlation of TMCP processing, microstructures and mechanical properties in the NV-F460 class shipbuilding plates. $50$ mm thick plates with room temperature yield-strength greater than $460$ MPa, and assured low temperature CVN toughness of $\sim 300$ J even at $-80^\circ$C were produced providing a new area for the technology. The microstructural factors were characterized and quantitatively correlated with the ductile-brittle transition temperature in the industrially produced steel plates.

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Al</th>
<th>Nb+V+Ti</th>
<th>Cu+Ni+Cr</th>
<th>$C_{eq}$</th>
<th>$P_{cm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.062</td>
<td>0.23</td>
<td>1.47</td>
<td>0.008</td>
<td>0.002</td>
<td>0.040</td>
<td>0.094</td>
<td>0.60</td>
<td>0.38</td>
<td>0.17</td>
</tr>
</tbody>
</table>

i.e., hot deformation at austenite recrystallization region and non recrystallization region with systematically varied finish rolling reduction ratio (FR) of 44%, 63% and 69%, was conducted. For convenience, the plates are referred as FR44, FR63, and FR69, in accordance with the low (44%), moderate (63%) and high (69%) FR, respectively.

Polished surface along thickness (ND) and finish rolling direction (RD) at center thickness ($t/2$) and quarter thickness ($t/4$) was etched in a 4% nital solution and observed by an optical microscope (OM) and a field emission scanning electron microscope (SEM) equipped with an EBSD camera (FEI’s model Quanta 3D FEG). The EBSD analysis (resolution: 0.2 $\mu$m) was conducted and the data were then interpreted by HKL technology Channel 5 software. These samples were also subjected to micro-hardness measurements at 10 kg load employing a digital closed-loop controlled Vickers hardness tester (model: Tukon 2100B, Instron). To examine the cleavage fracture facets, the fractured surfaces of the CVN samples fractured at $-196^\circ$C were observed by the SEM.

Mechanical properties in transverse-direction (TD) and RD at $t/2$ and $t/4$ were tested for the 45 and 50 mm plates. Round tensile samples with 8 mm gage diameter were machined and tested at room temperature at a crosshead speed of 5 mm/min by a 250-kN Instron machine (model Instron 5585H, Instron Corp., Canton, MA). The yield strength was measured at the 0.2% offset stress. CVN impact tests were performed on standard samples (size: $10\times10\times50$ mm) with the V notch parallel to ND at $-196^\circ$C to 0$^\circ$C by a 450-J instrumented pendulum impact tester (model IMP450J Dynatup, Instron). A regression analysis for absorbed impact energy versus test temperature was conducted with a hyperbolic tangent curve fitting method.

The hot rolled plates were further heat treated under strain aging conditions. For that, samples were taken at $t/4$ of the plates in RD and TD and subjected to elongation strains ($\varepsilon_t$) of 5% and 10%, respectively, and then aged at 250$^\circ$C for 1 h. Standard CVN samples were tested at $-60^\circ$C.

To investigate the microstructure and properties of the coarse grained heat affect zone (CGH A Z) of welds, rectangular specimens of $10\times10\times75$ mm were made from the $50$ mm thick plate (FR69) in 10 mm sections of the plate at $t/4$ and $t/2$. The HAZ simulations were performed using a Gleeble 3800 thermomechanical simulator employing the Rykalin-3D (thick plate) heat transfer model. A Pt-10 pct Rh thermocouple was spot welded at the central length of the specimens for recording the temperature. The specimens were heated at 130°C/s to a peak temperature ($T_p$) of 1350°C, held, for 0.1 second, and cooled at different cooling times for the stipulated range of 800°C to 500°C ($t_{w-c}$) to be equivalent to a weld heat input of 1.5 to 30.0 kJ/mm. CVN specimens were made with the notch at the central length, i.e., the spot welded thermocouple position along the original ND-TD orientation of
the plates, and the CVN impact energies were measured at -60°C in the same way aforementioned.

3. Results

3.1. Industrial TMCP-AcC Process

Key TMCP-AcC parameters for each plate investigated including the total rough rolling reduction ratio (RR), the total FR, finish rolling entry temperature (T\textsubscript{in}), exit temperature (T\textsubscript{out}), AcC cooling rate (φ) and AcC finish temperature (T\textsubscript{f}) are listed in Table 2. All the recorded temperatures were measured on the plate top surface. Rough rolling was finished at temperatures higher than 980°C resulting in 90 mm, 120 mm and 160 mm thick transfer bars. The transfer bars were held and cooled on the cooling bed (delay) to meet finish-rolling temperature, and then finish-rolled as plates FR44, FR63 and FR69, respectively.

Austenite hot deformation constitutive behaviour and static recrystallization have been studied for the NV-F460 grade shipbuilding steel. A peak strain observed on the static recrystallization have been studied for the NV-F460 rolled as plates FR44, FR63 and FR69, respectively.

The results are presented in Fig. 2 where the peaks on stress-strain curves which indicated the start of dynamic recrystallization was 0.35 at 1100°C at the strain rate of 1 s\textsuperscript{-1}. Stress-strain curves of austenite with a grain size (d) of 100 μm were measured at 1150 and 1200°C in the present work employing the same approach described in Ref. [18]. The results are presented in Fig. 2 where the peaks on stress-strain curves indicate the occurrence of dynamic recrystallization. According to the individual pass rolling schedules (the maximum pass strain was less than 0.22 with strain rates of 2 to 4 s\textsuperscript{-1}, which is less than the peak strains), therefore, static recrystallization should be the dominant softening and grain refinement mechanisms during rough rolling for which the solute drag mechanism of microalloying elements is taken into account at temperatures higher than 950°C. As expected, work-hardened (pancaked) austenite microstructure is achieved during finish rolling.

Table 2. Key TMCP-AcC parameters in the industrial rolling trials.

<table>
<thead>
<tr>
<th>Plate No.</th>
<th>Rough Rolling</th>
<th>Finish Rolling</th>
<th>Accelerated cooling (AcC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR44</td>
<td>50.0</td>
<td>72.0</td>
<td>835</td>
</tr>
<tr>
<td>FR63</td>
<td>45.0</td>
<td>63.0</td>
<td>855</td>
</tr>
<tr>
<td>FR69</td>
<td>50.0</td>
<td>50.0</td>
<td>777</td>
</tr>
</tbody>
</table>

Fig. 2. Flow stress behaviour of austenite observed during single hit compression tests at the deformation condition as indicated.

3.2. Microstructure

For the 50 mm plate FR44, the results of microstructure characterization are shown in Figs. 3 and 4. The OM image (Fig. 3(a)) along the ND×RD section at t/2 presents the microstructures consisted of fine QPF grains, predominance of coarse GB associated with secondary phases (Fig. 3(b)) which were identified by SEM as martensite-austenite (MA) constituents. The sample used for the OM and SEM observations was further examined by EBSD analysis. The orientation image map (OIM) with high-angle (∼15 deg) grain boundaries marked in dark lines indicates the coexistence of fine QPF grains (∼6 μm) and coarse GB colonies at approximately 70 μm at the t/2, as shown in Fig. 4. The subgrains in the coarse GB formed in identical austenite grain have similar crystallite angles to one another and thus the effective grain size of the GB is large.

Figures 5(a) and 5(b) are OM micrographs of plate FR69 with FR of 69%. Various phases presented in the microstructures are marked in the micrographs. The Vickers hardness (HV) data are also indicated. The microstructures at the t/4 section are more refined than those at the t/2 leading to higher hardness. The near surface materials may be exposed to the cooling rate which is faster than that of the bulk resulting in finer microstructure and higher hardness. The effect of FR on microstructure has been revealed by comparing the microstructures in Figs. 3 and 5. The FR of 69% led to the predominance of AF+QPF and refined GB in plate FR69. The secondary phases are mainly degenerate pearlite (DP) instead of MA constituents as it is the case for plate FR44. Inverse pole figure (IPF) maps obtained by EBSD analysis are shown in Figs. 6(a) and 6(b) for t/2 and t/4. The effective grain size of GB is refined to approximately 20 μm at t/2 due to the increased FR.

Figures 7(a) and 7(b) are OM images showing AF and DUB grains in plate FR63 at t/2 and t/4. SEM images, showing the difference of the microstructures at t/2 and t/4 and the secondary phases of DP, are given in Figs. 7(c) and 7(d).
The microstructure at \( t/4 \) is finer than that at \( t/2 \). IPF map obtained by EBSD analysis at \( t/2 \) is shown in Fig. 8. Coarse DUB grains are observed which formed in elongated (pan-caked) austenite grains with low angle grain boundaries.

### 3.3. Mechanical Properties

The mechanical properties including yield strength (\( YS \)), ultimate tensile strength (\( UTS \)), total elongation (\( EL \)), yield ratio (\( YR=YS/UTS \)) and CVN impact energies measured at \(-40^\circ C\) to \(-80^\circ C\) are given in Table 3.
The room temperature tensile properties of all the plates investigated met the specification for NV-F460 steel. Figure 9 shows room-temperature stress-strain curves of the plates. Plate FR44 shows a continuous yielding behavior. This is due to the high fraction of MA constituents (see Fig. 3) which promotes mobile dislocations at boundaries between the hard secondary phases and the nearby soft phases. Other plates show discontinuous yielding behaviour because of less MA particles as observed in Figs. 5 and 7. The effect of rolling process on the yield strength may be negligible. The YS at t/4 is, however, 40–60 MPa higher than that at t/2 which is consistent with the previous microstructure observations and hardness measurements for all the plates.

The increase of FR during rolling leads to significant improvement on the CVN performance. Brittle fractures were observed during Charpy impact testing at temperatures below −40°C showing CVN impact energies lower than 31 J in plate FR44. As a result, the plate cannot meet the minimum requirement for NV-F460 grade. In the other two plates (FR63 and FR69), the CVN impact energies at −60°C were well above the 31-J, exceeding the minimum requirement for F460 steel. The CVN impact performance at t/4 is generally better than that at t/2 (see CVN energies measured at −80°C). Some CVN samples taken from the FR69 plate, however, exhibited ductile fracture behaviour with impact energy ranged from 150 to ~300 J even under the strain aging conditions.

The curves of CVN impact-load combined with impact-energy versus hammer displacement were plotted and analyzed according to the data recorded by the instrumented Charpy machine. 20–22 The effects of tested temperature and strain aging on the CVN impact properties are shown in Figs. 11(a) and 11(b). The CVN samples taken from plate FR44 exhibited different load-displacement behaviours at the temperatures of 0°C and −40°C (see Fig. 11(a)). A ductile behaviour was observed at 0°C, where a 70-J crack-initiation energy, a 150-J crack-propagation energy and a 100-J post fracture energy were differentiated from the curves. The post fracture energy may be a measure of crack arrest capacity. A brittle behaviour was observed at −40°C, indicating that the absorbed energy in association with only the crack-initiation stage without energy consumed during the abrupt brittle crack. In Fig. 11(b), the CVN load-displacement plots are given for the samples taken from RD- 1/4 t of plate FR69 tested at −60°C, −80°C, strain-aged with 10%

### Table 3. Mechanical properties of the plates produced by the industrial-scale rolling trials.

<table>
<thead>
<tr>
<th>Plate No.</th>
<th>Location</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>EL (%)</th>
<th>CVN absorbed energy (J)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR44</td>
<td>TD-1/2</td>
<td>472</td>
<td>613</td>
<td>23</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45</td>
<td>28</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>FR44</td>
<td>TD-1/4</td>
<td>545</td>
<td>645</td>
<td>23</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td></td>
<td>92</td>
<td>13</td>
<td>13</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 4.

(a) FR44, t=50 mm

(b) FR63, r=45 mm

(c) FR69, r=50 mm

The curves of CVN impact-load combined with impact-energy versus hammer displacement were plotted and analyzed according to the data recorded by the instrumented Charpy machine. 20–22 The effects of tested temperature and strain aging on the CVN impact properties are shown in Figs. 11(a) and 11(b). The CVN samples taken from plate FR44 exhibited different load-displacement behaviours at the temperatures of 0°C and −40°C (see Fig. 11(a)). A ductile behaviour was observed at 0°C, where a 70-J crack-initiation energy, a 150-J crack-propagation energy and a 100-J post fracture energy were differentiated from the curves. The post fracture energy may be a measure of crack arrest capacity. A brittle behaviour was observed at −40°C, indicating that the absorbed energy in association with only the crack-initiation stage without energy consumed during the abrupt brittle crack. In Fig. 11(b), the CVN load-displacement plots are given for the samples taken from RD- 1/4 t of plate FR69 tested at −60°C, −80°C, strain-aged with 10%
elongation strain ($\varepsilon_e$) and tested at –60°C. All the samples demonstrated ductile-fracture behaviour. The absorbed energy at crack-initiation stage was 60 J for all the samples. The energies absorbed during crack-propagation were 270 J, 243 J and 233 J, respectively, for the three tested conditions. The post-fracture energy for the strain aged sample was 60 J at –60°C.

Figures 12(a) and 12(b), 13(a) and 13(b) show SEM fractographs of the CVN samples at $t/2$ and $t/4$ taken from plates FR63 and FR69, respectively, fractured at –196°C. The feature of the cleavage surface is dependent upon the microstructures of each sample. At $t/2$ of plate FR63 where coarse DUB grains were observed, large cleavage facets sized ~50 μm were found (Fig. 12(a)). The lath structure and inter-lath bright particles indicate that the large cleavage facet originated from a coarse DUB. At $t/4$ of plate FR63 where more elongation strain ($\varepsilon_e$) and tested at –60°C.
refined microstructures were observed (see Fig. 7), the maximum size of cleavage facets were reduced to ~20 μm (Fig. 12(b)). Because the microstructures are more refined in plate FR69, the size of the maximum cleavage facet is below 20 μm at t/2 and 10 μm at t/4, as shown in Fig. 13. Large cleavage facet is associated with long unit crack propagation path and reduced ductile crack resistance. Fine-grained QPF, AF and refined DUB/GB are therefore required to decrease the ETT in the advanced plates.

4. Discussion

4.1. TMCP Process

Advanced heavy plates with YS of 460 MPa and secured ductile fracture at –60°C, i.e., NV-F460 steel plates, are produced in the present work. Integrated TMCP-AcC specification has been defined to produce advanced F460 thick plates with the thickness of 45 to 50 mm based on the results of a series of industrial rolling. For the two-stage controlled rolling, one of the key process parameters is the FR of minimum 63% to produce heavily work-hardened and non-recrystallized austenite to facilitate the transformation into fine-grained QPF, AF and refined DUB/GB microstructures during AcC. The best mechanical properties are achieved in plate FR69 with the highest FR. Long delay time is unavoidable during rolling, and hence sequential multiple-plates cross rolling strategy is recommended (e.g., three plates are simultaneously on delay while one plate is being rolled). The productivity can be improved by 300% compared with single plate rolling method in mass production. In addition, AcC process is another key process step which should ensure the entire continuous cooling transformation completed at the defined cooling rates. 18)

4.2. Effect of Microstructure Factors on Mechanical Properties

The microstructures vary when the FR changes in the austenite non-recrystallization region. Different microstructures are also observed at different locations across the plate thickness that results in the difference in mechanical properties. For example, coarse GB/DUB microstructures (Figs. 3 and 12) deteriorate the low temperature toughness while refined QPF/AF grains yield the best combination of strength and low temperature toughness in the heavy plates (see Fig. 13).

The microstructure factor, i.e., the distribution of grain-boundary misorientations taken from each EBSD measurement (see Figs. 4, 6 and 8) is quantified as shown in Figs. 14(a) through (d). The average grain-boundary angle

Fig. 12. SEM fractographs of Charpy impact samples fractured at –196°C taken from plate FR44 at (a) t/2, and (b) t/4.

Fig. 13. SEM fractographs of Charpy impact samples fractured at –196°C taken from plate FR69 at (a) t/2, and (b) t/4.

Fig. 14. Distribution of grain-boundary misorientations of (a) plate FR44 at t/2, (b) plate FR69 at t/2, (c) plate FR69 at t/4, and (d) plate FR63 at t/2.

Fig. 12. SEM fractographs of Charpy impact samples fractured at –196°C taken from plate FR44 at (a) t/2, and (b) t/4.

Fig. 13. SEM fractographs of Charpy impact samples fractured at –196°C taken from plate FR69 at (a) t/2, and (b) t/4.

Fig. 14. Distribution of grain-boundary misorientations of (a) plate FR44 at t/2, (b) plate FR69 at t/2, (c) plate FR69 at t/4, and (d) plate FR63 at t/2.
(AGBA) and the fraction of high-angle grain boundaries (HAGB, which is greater than 15 deg) are also indicated. The AGBA and the fraction of HAGB increase as the FR increase, leading to more refined microstructures. Furthermore, the AGBA and the fraction of HAGB at \( t/4 \) are greater than those at \( t/2 \). The corresponding ETT data (TD-\( t/2 \) of plate FR44, RD- \( t/2 \) of plate FR63, TD- \( t/2 \) and \( t/4 \) of plate FR69) are linearly correlated to the AGBA, and the fraction of HAGB, as shown in Figs. 15(a) and (b). The high AGBA and the high fraction of HAGB are correlated to low ETT. The ETT is more dependent on the AGBA than on the fraction of HAGB. Similar trends were found by Han et al.\(^9\) in the experimental X80 steels. The present study, however, indicates that the ETT of the industrial NV-F460 plates is more sensitive to the microstructure factors, i.e., the AGBA and the fraction of HAGB, because larger absolute slopes are observed (see Fig. 15) than these observed by Han et al.\(^9\) The above analysis emphasizes once again the significance of applying heavy FR to facilitate the formation of fine microstructures with small effective grain size, high AGBA, and high fraction of HAGB. Insufficient FR leads to the formation of coarse DUB and GB microstructures with low AGBA, low fraction of HAGB, which are detrimental to the low temperature toughness and give rise to high ETT.

4.3. Weldability

The coarse-grained heat affected zone (CGHAZ) adjacent to the fusion line has the lowest toughness within the HAZ because of large prior austenite grains. Appropriate heat input must be employed during welding to control the microstructures produced during continuous cooling and mechanical properties of the CGHAZ. Table 5 shows the hardness, CVN impact toughness measured under various heat input conditions. Either the hardness or the CVN absorbed energy decreases as the heat input increases. When the heat input is 1.5 to 3.0 kJ/mm, excellent toughness values are observed even at –60°C. At 5.0 kJ/mm and above, however, the impact toughness decreases substantially, not achieving the targets as defined for the parent F460-steel plates. The microstructures of the bulk materials at \( t/2 \) corresponding to different CGHAZ conditions are shown in Fig. 16. Similar series of microstructures were observed in

![Graph](image1)

**Fig. 15.** Relationship between (a) ETT and average grain boundary angle, (b) ETT and the fraction of high-angle grain boundaries.

<table>
<thead>
<tr>
<th>Thickness ( t ) (mm)</th>
<th>Location</th>
<th>Heat input (kJ/mm)</th>
<th>( T_T ) (°C)</th>
<th>( t_{\text{CVN}} ) (s)</th>
<th>Hardness (HV)</th>
<th>CVN absorbed energy at –60°C (J)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t/2 )</td>
<td>1.5</td>
<td>1350</td>
<td>3.9</td>
<td>310</td>
<td>341 (309)</td>
<td></td>
</tr>
<tr>
<td>( t/4 )</td>
<td>1.5</td>
<td>1350</td>
<td>3.9</td>
<td>316</td>
<td>362 (331)</td>
<td></td>
</tr>
<tr>
<td>( t/2 )</td>
<td>3.0</td>
<td>1350</td>
<td>7.7</td>
<td>278</td>
<td>254 (207)</td>
<td></td>
</tr>
<tr>
<td>( t/4 )</td>
<td>3.0</td>
<td>1350</td>
<td>7.7</td>
<td>276</td>
<td>321 (285)</td>
<td></td>
</tr>
<tr>
<td>( t/2 )</td>
<td>5.0</td>
<td>1350</td>
<td>12.9</td>
<td>254</td>
<td>179 (105)</td>
<td></td>
</tr>
<tr>
<td>( t/4 )</td>
<td>5.0</td>
<td>1350</td>
<td>12.9</td>
<td>253</td>
<td>74 (21)</td>
<td></td>
</tr>
<tr>
<td>( t/2 )</td>
<td>10.0</td>
<td>1350</td>
<td>25.7</td>
<td>230</td>
<td>32 (22)</td>
<td></td>
</tr>
<tr>
<td>( t/4 )</td>
<td>10.0</td>
<td>1350</td>
<td>25.7</td>
<td>230</td>
<td>25 (23)</td>
<td></td>
</tr>
<tr>
<td>( t/2 )</td>
<td>30.0</td>
<td>1350</td>
<td>77.2</td>
<td>205</td>
<td>11 (9)</td>
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<tr>
<td>( t/4 )</td>
<td>30.0</td>
<td>1350</td>
<td>77.2</td>
<td>207</td>
<td>11 (10)</td>
<td></td>
</tr>
</tbody>
</table>

* Average energy of three specimens followed by parentheses with the minimum value.

![Graph](image2)

**Fig. 16.** The effect of heat input on microstructures in the CGHAZ conditions.
the samples taken from t/4. At 1.5 kJ/mm, the microstructures are mainly LB+LM that have high fraction of high angle grain boundaries and reduced effective grain size, as a result, give rise to the high strength (hardness) and enhanced ductile fracture resistance. At 3.0 kJ/mm, similar microstructure and hardness are observed that lead again to excellent toughness even at –60°C. At 5.0 kJ/mm and above, however, microstructures are featured by UB+GB associated with coarse M/A constituents, that have low fraction of high angle grain boundaries and large effective grain size, leading to decreased hardness and toughness. The present study suggests that the upper limit of heat input during welding practice for the investigated plate is 3.0 kJ/mm, which is generally consistent with the early study.

5. Conclusions

The effect of process parameters of industrial production on microstructure and mechanical properties in a microalloyed SiMnCrNiCu steel with lean composition has been investigated to commercially produce heavy (45–50 mm thick) plates of NV-F460 grade via thermomechanical control process (TMCP) for offshore structures and shipbuilding:

1. Key TMCP parameters are determined to be (a) applying minimum 63% finish rolling reduction ratio in austenite non-recrystallization region (T<sub>top</sub> ≤ 850°C) followed by (b) accelerated cooling to ensure phase transformation completed before (c) the interrupted cooling at 460°C on the plate surface.

2. Best mechanical properties are achieved when 50 mm thick plate is rolled heavily at 69% finish rolling reduction ratio in austenite non-recrystallization region. The room temperature yield strength exceeds 460 MPa, and CVN impact energies range from 150 J to 300 J even at –80°C with ductile fracture behaviour.

3. The finish rolling reduction ratio affects the final microstructure and mechanical properties of the heavy plates significantly. At 44%, coarse granular bainite and degenerate upper bainite associated with MA constituents are formed across the plate thickness. At 63%, acicular ferrite grains are dominant, but coarse degenerate-upper-bainite grains of 40 μm are still observed at center thickness. At 69%, fine-grained quasipolygonal ferrite and acicular ferrite, refined degenerate-upper-bainite/granular-bainite grains and degenerate-pearlite are produced as main secondary phases. The microstructures at quarter thickness are finer than those at center thickness leading to increased fraction of high angle grain boundaries.

4. The fractographs revealed by SEM indicate that coarse degenerate-upper-bainite grains create large cleavage facets leading to deteriorated CVN properties. The low temperature CVN properties are improved by the formation of fine quasipolygonal ferrite, acicular ferrite and refined degenerate-upper-bainite/granular-bainite with high angle grain boundaries due to increased finish rolling reduction rate.

5. Linear relationships are found between the energy transition temperature and the average grain boundary angle, and the energy transition temperature between the fraction of high-angle grain boundaries in the industrially produced NV-F460 plates.

6. The upper limit of heat input during welding is 3.0 kJ/mm to secure the CVN toughness of the coarse grained heat affect zone at –60°C.

The above results, (1)–(6) have made it possible to industrially produce NV-F460 heavy plates.

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