Development of Innovative Heavy-Gauge 38.5-mm X80 Pipeline Steel Plate Designed Via High Niobium

Zhang Yongqing1, Nie Wenjun2, Zhang Chuanguo3, David Han4,5, Xiaodong He6, Aaron Litschewski2, Roney Lino5

1CITIC Metal Co., Ltd.
Beijing 100004, P.R. China
2Shagang Steel & Iron Trade Co., Ltd,
Zhangjiagang Bonded Area, Jiangsu, 215625, P.R. China
3Baosteel Central Research Institute
Shanghai 201900, P.R. China
4International Welding Technology Center
Xi’an 710077, P.R. China
5CBMM
São Paulo 04538-133, Brazil
6CNPC Tubular Goods Research Institute
Xi’an 710077, P.R. China

ABSTRACT
Since the Second West-East Pipeline Route in P.R. China in 2008, the X80 steels with the design via low carbon (<0.07 wt.%) and high niobium (Nb) (>0.07 wt.%) have been the mainstream products for the long-distance high-pressure natural gas pipeline projects. Aiming at dramatic increased delivery value of natural gas, both wall thickness and pipe diameter for X80 pipeline steel plate have reached up to current 38.5 mm and 1,422 mm, respectively, which uses innovative design of chemical composition and rolling procedure. In this study, the metallurgical design through chemical composition of high Nb and optimized rolling procedure have been relied on for qualified heavy-gauge 38.5 mm X80 via industrial trial. Meanwhile, the weldability and girth welding of OD1,422 mm × 38.5 mm X80 steel pipes have been investigated and assessed. With the increasing of pipe wall thickness, the addition of high Nb into X80 is a reasonable methodology to guarantee the key performances, including drop weight tear test (DWTT), ductile-brittle transition temperature (DBTT) as well as yield-to-tensile (Y/T) ratio after the deformation to a large extent during pipe making. Further, the girth welding with both GMAW (STT – Tension Surface Transfer) + GMAW has been conducted to evaluate the influence of high Nb on fusion line (FL) & heat-affected zone (HAZ) of the obtained welded joints. The results demonstrate that the Nb microalloying is beneficial to improve the performances of pipe body as well as girth welds, especially for such a heavy-gauge 38.5 mm X80 steel pipe.

Key words: Nb microalloying, 38.5 mm heavy-gauge X80, DWTT, DBTT, Y/T ratio, weldability, girth welding

INTRODUCTION
In order to satisfy the increased requirement for natural gas transmission, China has planned and constructed a couple of huge projects, such as China-Russia Pipeline Route, West-East Pipeline Route, and China-Myanmar Pipeline Route. After developing for 15 years, the current pipeline industry is continuously working on the optimization in designing pipeline steels, aiming at cost efficiency and high quality. The drive for the optimization is from the market for this steel group, which requires
higher strength and fracture toughness performance in heavy gauge and large diameter [1]. Modern high-strength heavy plates
used in the production of large diameter line pipes are generally produced by thermo-mechanical controlled processing (TMCP)
[2, 3], and the combination of high strength and high fracture toughness of these steel plates is a result of the reasonable
microstructure realized through TMCP, which is strongly influenced by steel compositions as well as rolling and cooling
conditions [4]. High-strength low-alloyed (HSLA) steels are microstructurally tailored to meet the demanding requirements of
satisfying performance [5], involving grain refinement in conjunction with microstructural and precipitation control for a
certain industry. The pipe steels of interest in this investigation contain nominally high Nb, i.e. ~0.095 wt.%, and the weld
metal will contain lower levels of Nb through base plate dilution [6]. The scale of 1,422 mm in diameter and 38.5 mm in wall
thickness is the largest one designed in the world currently. This product was developed based on the study of OD1,422 mm ×
32.1 mm X80 steel pipe, and has a potential application in the fourth West-East Pipeline Route. Besides the diameter and
thickness, the maximum length for the designed 38.5 mm X80 pipe is 12.3 m.

MATERIALS AND EXPERIMENTAL PROCEDURES

The materials in this study are the X80 SAWL (longitudinal submerged arc welding) pipes with a dimension of OD1,422 ×
38.5 mm manufactured with two designed production procedures by the steel mill of the Shagang Group. And the pipe makers
for these two 38.5 mm X80 pipes were manufactured by Qingxian Julong pipe mill and Nanjing Julong pipe mill. The
specimens from two pipe mills were named as SG-JL and SG-NJ, respectively. The images of two pipes can be seen in Fig. 1,
and the produced pipe is according to the PipeChina Design & Engineering Code (DEC), i.e. DEC-NGP-S-PL-003-2020-1,
Specification of Steel Pipe for Gas Pipeline Project.

In the metallurgical design of OD1,422 mm × 38.5 mm X80 steel pipe, three major stages have been focused on, aiming at the
key performance with the increased wall thickness and width of the plate. Three stages include steel development (alloy design,
processing optimization), pipe making (performance adjustment, submerged arc welding), and girth welding. In order to play
the full role of Nb, and improve the performance, the production optimization of SG-NJ with high Nb contents, especially
relying on target per pass reductions for austenite refinement and strain-induced Nb precipitation, was designed to control as
two important stages: 1) austenite refinement + start of Nb strain-induced precipitation through last roughing mill (RM) pass;
2) austenite refinement + continuous robust Nb strain-induced precipitation for optimum volume and final distribution/size
through first 3 ~ 4 finish mill (FM) passes. In addition, the steel plate of SG-JL was produced according to the regular rolling
procedure in Shagang.

The chemical composition of two studied pipe steels is listed in Table 1, and the Pcm values of two steels are calculated using
Eq. 1.

<table>
<thead>
<tr>
<th>No.</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>Nb</th>
<th>Ti</th>
<th>N</th>
<th>Pcm</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG-JL</td>
<td>0.051</td>
<td>0.2</td>
<td>1.69</td>
<td>0.16</td>
<td>0.14</td>
<td>0.28</td>
<td>0.094</td>
<td>0.014</td>
<td>0.0040</td>
<td>0.173</td>
</tr>
<tr>
<td>SG-NJ</td>
<td>0.056</td>
<td>0.2</td>
<td>1.72</td>
<td>0.16</td>
<td>0.15</td>
<td>0.28</td>
<td>0.093</td>
<td>0.014</td>
<td>0.0039</td>
<td>0.180</td>
</tr>
</tbody>
</table>

\[
P_{cm} = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B
\]
From Eq. 1, it can be understandable that the element of Nb has no influence on P_{cm}. Even if there is no difference in weldability theoretically, this study will investigate the difference in weldability due to customised design of original microstructure and Nb precipitation.

The specimens for two studied steel pipes were prepared for microstructure analysis. The longitudinal sections (rolling direction, RD) of the specimens were observed using optical microscopy (OM) Olympus OLS5000. In order to precisely characterize precipitates, the methodologies of dissolution/filtering and SAXS (small angle X-ray scatter) to analyze particle distribution. Further, on the basis of microstructure analysis, the key performance with increased wall thickness, including drop weight tear test (DWTT), ductile-brittle transition temperature (DBTT) as well as yield-to-tensile (Y/T) ratio after the deformation to a large extent during pipe making. Meanwhile, the weldability and the performance of seam & girth welds have to be maintained and even improved after a multi-pass welding with higher heat input with increased wall thickness.

**RESULTS AND DISCUSSIONS**

As displayed in Fig. 2 and Table 2, the microstructures for two steel pipes at the locations of surface, 1/4 wall thickness and 1/2 wall thickness are here when the specimens were taken from 180° from seam weld, and the sampling direction is along transverse. Table 2 offers the comparison of microstructure, grain size, etc. Be noted that GB stands for granular bainite, PF is polygonal ferrite, and M-A is martensite-austenite constituent.
On the basis of acceptable metallurgical quality in respect to inclusion and banded structure for both steel pipes, the comparison of their microstructure and performance is turning to be meaningful. From the above results, it is evident that more refined grains can be observed near surface of the pipes. Comparatively, SG-JL has more refined grain sizes at all three locations compared to SG-NJ, and the difference is 0.5 grade. Further, due to the difference in the RM, FM passes and cooling procedures, two steels are not very same in microstructure due to the fraction of PF and appearance of M-A. From the subsequent performance-related results, it can be understood that the existing M-A in SG-JL has not impacted its pipe performance.

The samples for tensile tests were taken at the location of 180° from seam weld, whose direction is transverse. Here, the round bar samples with three dimensions of Dia. × Gauge length were selected, i.e. Φ12.7 mm × 50 mm, Φ20 mm × 50 mm and Φ25 mm × 50 mm, which only set the gauge length of the tensile sample in the DEC requirement for such as a thickness. The sampling location for tensile tests is shown in Fig. 3, and Fig. 4 gives the results. All samples were taken from the centre wall thickness of the pipes.
From Fig. 3 and Fig. 4, it is comparatively seen that with all three dimensions, the Y/T ratios of SG-NJ are higher than that of SG-JL, and all values are exceed 0.93, which has been limited to below some percentage of all pipes for the practical construction. There is no conclusion regarding the correlation between Y/T ratio and dimension. And in this case, the samples with highest Y/T ratios are 0.932 for SG-JL and 0.966 for SG-NJ, respectively. The reason from Fig. 4 can be ascribed to the local yield strength values for these two samples, which are 635 MPa and 641 MPa, respectively. These two values are higher than any yield strength by the samples with different dimensions. However, from the overall results, the range of 622 MPa to 641 MPa is reasonable for the yield strength for two pipes. But SG-NJ has an apparent lower ultimate tensile strength compared to SG-JL, i.e. 662 ~ 664 MPa vs 681 ~ 684 MPa. The different contributions to yield strength and ultimate tensile strength via varied strengthening mechanisms for SG-JL and SG-NJ are different based on the results. Since high Nb, i.e. ~0.095 wt.%, was used to produce the pipe steels, the possible contribution of related factors to the strengthening of two studied steels are listed in Table 3.

<table>
<thead>
<tr>
<th>Strengthening factors</th>
<th>SG-JL</th>
<th>SG-NJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain boundary strengthening</td>
<td>Higher</td>
<td>Lower</td>
</tr>
<tr>
<td>Dislocation density</td>
<td>Higher</td>
<td>Lower</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Lower</td>
<td>Higher</td>
</tr>
<tr>
<td>Solution</td>
<td>Equal</td>
<td>Equal</td>
</tr>
</tbody>
</table>

Table 3 Qualitative comparison of strengthening contribution of different factors
Based on Ref. [7], the contribution of grain boundary, dislocation density and precipitation strengthening on yield strength is more than ultimate tensile strength, however, the contribution of solution strengthening is opposite. The comparison of four strengthening factors can be seen from Table 2, and the trend of dislocation density is generally consistent with grain size.

However, CEIT (Centro de Estudios e Investigaciones Técnicas) has obtained the different results with the above tensile results from TGRI. Since the sample sizes have not been mentioned in the CEIT’s technical report [8], there is no clue that whether these two data resources are comparable. What has to be pointed out here is that based on the results from CEIT, 1) SG-NJ has a higher Y/T ratio compared to SG-JL. But more than half of Y/T ratios are lower than 0.93; 2) The samples from the head of the plate have a higher Y/T ratio than that from the tail.

The EBSD results by CEIT regarding the low and high angle misorientation were displayed in Fig. 5. Here, the low angle misorientation criteria was set to be (4 ~ 15°), and the high angle misorientation criteria to be >15°. It is well understood that the grains with low angle misorientation corresponds to the unit size controlling tensile properties.

A useful parameter to evaluate the tail length of a distribution is the critical grain size named as Dc20%, which refers to the cutoff grain size at 80% area fraction in a grain-size distribution histogram, seen in Fig. 6. In order to quantify the effect of microstructural heterogeneity, the ratio between Dc20% and D15° was estimated. Be noted in Fig. 6, SG-JL is X80 2021, and SG-NJ is X80 Optimized 2022. Table 4 summarised the AVG grain size, Dc20% and Dc20%/D15°. It is evident that lower Dc20%/D15°, i.e. 6.3, was measured for SG-NJ in the center location, being compared with 16.4 of SG-JL, and reflecting the formation of more homogeneous microstructure.

© 2024 by the Association for Iron & Steel Technology.
According to the results of SAXS, the SG-NJ sample has two major types of phases, i.e. Nb(C, N) and Ti(C, N), and both of them are face-centred cubic (FCC) structures. From the results, the lattice constant (nm) of Nb(C, N) and Ti(C, N) in SG-NJ is 0.445 ~ 0.446 and 0.433 ~ 0.434, respectively. Table 5 gives the mass fraction of elements in M(C, N), and from this table, it is evident that 0.0646 wt.% Nb has been precipitated out based on the changed rolling procedures, and totally the elements of 0.0914 wt.% are in the precipitates in the case of SG-NJ.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Nb</th>
<th>Ti</th>
<th>Mo</th>
<th>Cr</th>
<th>C</th>
<th>N</th>
<th>Σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG-NJ</td>
<td>0.0646</td>
<td>0.0135</td>
<td>0.0006</td>
<td>0.0002</td>
<td>0.0077</td>
<td>0.0048</td>
<td>0.0914</td>
</tr>
</tbody>
</table>

The distribution of the collected particles in SG-NJ can be seen in Table 6, and most of particles are in the size range of 36 ~ 60 nm, i.e. 32.5 wt.%. And then 18 ~ 36 nm and 60 ~ 96 nm, i.e. 21.5 wt.% and 21.0 wt.% respectively. Total 75 wt.% particles are concentrated in the size range of 18 to 96 nm. Further, the mean size of the particles is 76.1 nm, and median size is 54.2 nm.

Even if there is no corresponding SAXS results regarding SG-JL, it can be understood that in the optimized production of SG-NJ, more effective precipitates have been found, which is beneficial to the subsequent welding processes since most of particles, i.e. 75 wt.%, are in the size range of 18 ~ 96 nm.

Another strengthening of solution is supposed to be similar for two steels since the reheating temperatures and durations during the production are similar for them.
The hardness distribution was conducted from the distance from 1.5 mm below the outer surface to 36.5 mm, which is near inner surface, shown in Fig. 7. Be noted that the interval of two adjacent points is 1 mm, and 10 mm was set for the width of A-A, B-B and C-C cross sections. Here the sampling locating is 180° from seam weld, and the direction is transverse.

![Fig. 7 Sampling location for hardness tests.](image)

From the results of hardness distribution (Fig. 8), it is clear that SG-JL has an overall higher hardness than SG-NJ, which is consistent with the results of ultimate tensile strength in Fig. 4. Beside this conclusion, it can be observed that the hardness close to the surface is higher, especially the inner surface. The contribution of hardness has a same trend with strength, especially ultimate tensile strength. And refined grain size is one of the key factors that determine the increasing of strength, which is the same reason for higher hardness near surfaces.

![Fig. 8 Hardness distribution at three locations.](image)

When compared the DBTTs by Charpy impact toughness of both steel pipes, the sampling location is 90° from seam weld (in transverse) at the centre wall thickness. Fig. 9 gives the results of DBTTs for two pipe bodies.

![Fig. 9 DBTTs by Charpy impact toughness.](image)

Compared to SG-JL, SG-NJ has a higher DBTT, which means SG-JL is better in impact toughness when the sampling occurred in the center wall thickness. However, both pipe bodies have a high Charpy impact toughness at $\geq -40 \, ^{\circ}C$, i.e. over 300 J. And at $-60 \, ^{\circ}C$, all single values of SG-JL are still higher, i.e. over 270 J. Meanwhile, SG-NJ has some low CVN values when tested at $-60 \, ^{\circ}C$. The better DBTTs of SG-JL to some extent has a relationship with the refined grain size in the 1/2 wall thickness of the pipe. The same conclusions can be obtained in respect to DWTT, when the test temperature was set to be $-40 \sim 20 \, ^{\circ}C$, two
samples for each pipe were performed to characterise the fracture. The full-thickness samples were taken in transverse at the location of 90° from seam weld, and the sample size is 305 mm × 76.2 mm × 38.5 mm.

Fig. 10 illustrates the DWTT results of two steels, and Fig. 11 shows the fracture surfaces of tested samples when tested at 0 °C. For full-thickness samples, at 0 °C SG-NJ has an AVG DWTT of 80%, and SG-JL keeps a high DWTT even at -20 °C. In sum, SG-JL is better than SG-NJ regarding the (single/AVG) DWTT values & DWTT data discretisation. And this can also be verified by the appearance of fracture in Fig. 11.

The girth welding of these two 38.5 mm X80 pipes was completed in the welding lab. And the combined (GMAW (STT) + GMAW) was selected for inside and outside welding, i.e. root pass + hot, fill and cap passes. And the joint design can be referred to in Fig. 12. In the welding job, the consumables used were the solid wire ER80S with the diameter of 1.0 mm, and the shielding gas is (20 vol.% CO2 + 80 vol.% Ar). The setting of weld layer (pass) for root, hot, fill and cap passes is: 3(3) + 1(1) + 9(9) + 1(2). Before performance testing, it is necessary to understand that the girth welding quality of heavy gauge pipe is difficulty to be controlled. But in order to save the consumable, the groove angle is still designed to be only 5°, which has created a lot of potential defects for the welding process.
After girth welding, the radiographic testing (RT) was performed as a non-destructive test (NDT) to prove that two girth welds are qualified, seen in Fig. 13. Among the series performance tests, some key ones, such as CVN/DBTT, hardness mapping, were selected to demonstrate the results of girth welding.

In order to compare the results with that from pipe body (Fig. 9), the sampling of the specimens for impact toughness were taken from the centre wall thickness of the pipes. And two key locations, i.e. FL (50% WM and 50% HAZ) and (FL + 0.5 mm) were used for a typical example. From Fig. 14, it can be known that the CVN data below 20 °C are quite scattered for such a thick pipe. Table 7 summarised the DBTT, USE (upper shelf energy) and LSE (lower shelf energy) results for pipe body, FL and (FL+0.5 mm) of two pipes. In general, two pipes and their girth welds have a good toughness, no matter DBTT or USE/LSE. The DBTT of < -45 °C is already an acceptable value for modern X80 pipes.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Description</th>
<th>DBTT</th>
<th>USE</th>
<th>LSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG-JL</td>
<td>Pipe body</td>
<td>-68 °C</td>
<td>470 J</td>
<td>10 J</td>
</tr>
<tr>
<td></td>
<td>Girth weld (FL)</td>
<td>-48.8 °C</td>
<td>270 J</td>
<td>20 J</td>
</tr>
<tr>
<td></td>
<td>Girth weld (FL + 0.5 mm)</td>
<td>-50.2 °C</td>
<td>235 J</td>
<td>30 J</td>
</tr>
<tr>
<td>SG-NJ</td>
<td>Pipe body</td>
<td>-58 °C</td>
<td>460 J</td>
<td>25 J</td>
</tr>
<tr>
<td></td>
<td>Girth weld (FL)</td>
<td>-77.5 °C</td>
<td>320 J</td>
<td>15 J</td>
</tr>
<tr>
<td></td>
<td>Girth weld (FL + 0.5 mm)</td>
<td>-58.8 °C</td>
<td>280 J</td>
<td>15 J</td>
</tr>
</tbody>
</table>
Another key test is hardness mapping, and Fig. 15 gives the results of hardness mapping for the obtained girth welds.

The over-matching pattern has been used when choosing the consumables for two girth welds. Comparatively, SG-JL has more softening trend considering the reduction of hardness at some areas, like Points 1, 3, 4 and 6. However, the most softening area for SG-NJ is Point 4, only -5 HV0.5.

The girth weld performance results regarding toughness and softening behaviour clearly clarify the better weldability of SG-NJ, which has more effective Nb-related precipitates. This reason is a major one that was generated from the design of both steels.

Two key regions for the girth weld include coarse grained HAZ (CGHAZ) and inter-critical coarse grained HAZ (ICCGHAZ). Both CGHAZs have the microstructure of GB, and both ICCGHAZs have a small amount of phases in chain, i.e. M-A constituent. Two points can be observed in comparison, including, 1) AVG grain size in CGHAZ of SG-NJ is smaller than SG-JL; 2) More chain microstructure, i.e. M-A constituent, can be observed in the ICCGHAZ of SG-JL from Fig. 16. However, the region of ICCGHAZ is too small to impact the final toughness of FL and (FL + 0.5 mm). And it should be noted that it is difficult to capture the totally same areas for two samples during the OM experiment.
CONCLUSIONS

The microstructure and key mechanical properties of two heavy-gauge 38.5 mm X80 steels with high Nb contents, and then their qualified girth welds were investigated in this study. The following conclusions can be drawn:

1. Two X80 pipes with high Nb microalloying, i.e. ~0.095% Nb, have expressed different microstructure and performance due to varied designed rolling procedures. The higher ultimate tensile strength of SG-JL enables its reasonable Y/T ratio. The precipitation strengthening improves the yield strength of SG-NJ to some extent, however, its ultimate tensile strength has not been increased to the expected degree accordingly, which has influenced the final Y/T ratio value.

2. Based on the EBSD results, SG-NJ has a more homogeneous microstructure compared to SG-JL, which is related to the effect of high Nb as well as the optimized hot rolling procedure.

3. The girth welds of the 38.5 mm X80 pipes can have an excellent performance even if more passes are needed for girth welding. And due to more passes applied in welding, more ICCGHAZs appear for the girth welds. However, such small areas of ICCGHAZ, which are detrimental to the performance of the welded joint, have not impaired the
toughness if they are not connective. The girth welds can still have a very good performance. Comparatively, SG-NJ has a better weldability due to more effective precipitates, which are beneficial to resist the grain growth and generation of chained M-A in the HAZs.

4. In total, the high Nb content (~0.095%) can guarantee the microstructure and performance of 38.5 mm X80 pipes, and the effective Nb-related precipitates are beneficial to girth welding.

Acknowledgements: This work is financially supported by CITIC Metal and CBMM, and technically supported by Shagang, Baosteel, IWTC and TGRI. In addition, Mr. Doug Stalheim from DGS Metallurgical Solutions, Inc. also provided big technical help for rolling schedule optimization.

REFERENCES


3. Z.X. Zhu, J. Han, H.J. Li, Effect of alloy design on improving toughness for X70 steel during welding, Materials and Design, 2015, 88: 1326-1333.


