Normalizing Rolling of Niobium Microalloyed Heavy-Gauge Plates for Wind Tower Applications

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ABSTRACT

Normalizing rolling is a thermo-mechanical controlled process that emulates the normalization heat treatment directly after the final rolling pass. It is an economically advantageous production route, however, the final microstructure does not bear the same characteristics as the offline heat treated material, especially for plate gauges above 50 mm. This work shows an innovative steel design for plates up to 76,20 mm in thickness, by adding larger amounts of Nb and lower quantities of C and Mn. This chemical composition was elaborated aiming the improvement of centerline segregation, microstructural homogeneity of the plate and proper Charpy impact toughness throughout the thickness of the rolled unit. For this assessment industrial slabs were rolled for evaluation of mechanical properties, microstructural features and welded joint characterization. Findings showed a much more homogeneous material in terms of microstructure and mechanical properties when compared to conventional structural steel for the same application.

Keywords: normalizing rolling; plate; heavy gauge, niobium

INTRODUCTION

The delivery condition "+N" (normalizing rolling) from EN10025-2 standard specifies structural plates used for the manufacturing of structures such as wind towers. This standard allows mills to utilize thermomechanical processing options considered equivalent to processing via heat treatment in an off-line furnace. The production of heavy gauge plates, for example greater than 50 mm, is a challenge for mills as the holding thickness for controlled rolling can exceed 100 mm. This causes inconveniences such as long waiting times before the finishing rolling stage and a greater temperature difference between the surface and the center of the sketch. These conditions represent a greater risk of obtaining microstructural heterogeneity throughout the thickness, which goes against the homogeneity provided by normalization heat treatment.

In addition to the effects on microstructural evolution caused by the temperature difference between the surface and center of the draft, another metallurgical risk comes into play: partial recrystallization. For alloys with conventional Nb contents, up to 0.040% by weight, the non-recrystallization temperature is predicted to be around 950°C, which is very close to the final rolling temperature for these steels in the +N condition. Working with lower finishing temperatures can cause work hardening of the pro-eutectoid ferrite, with rolling in the dual phase region on the colder surface, which produces a material metallurgically incompatible with the “Normalized” concept. On the other hand, with higher rolling temperatures, the risk of partial recrystallization occurring in the mid thickness position increases.

The qualification rules for EN10025-2 stablishes that Charpy specimens are taken from the surface of the plates, which makes the greater microstructural heterogeneity undetectable, in other words, the equivalency between normalizing rolling and normalization heat treatment becomes metallurgically very doubtful.

The possibility of obtaining intense microstructural heterogeneity between the surface and center of thicker plates, covered by the deficiency in the qualification rules of EN10025-2, is an opportunity for alloys with higher Nb content. An alloy design that defines a higher non-recrystallization temperature and higher Ar3 temperature (reducing Mn, for example) could solve this metallurgical impasse with advantages for the quality of heavy gauge plates and productivity during rolling of such plates.

RESULTS

1. Materials and Methods

Two heats with higher Nb content (here called HTP+N) were produced on an industrial scale and rolled into two thicknesses, 63 mm (HTP63) and 76 mm (HTP76). For comparison, 63 mm plates were also produced using a standard alloy (STD63). The chemical compositions are presented in table 1. During the rolling stage, all plates were finished at an aimed temperature above Ar3. For mechanical characterization, transverse tensile tests were carried out, before and after simulated normalization heat treatment, and longitudinal Charpy test pieces were taken from the surface, quarter and mid thickness positions, varying the test temperature from 0 to -40°C. Microstructural characterization was carried out using conventional optical microscopy. Samples from the 63 mm plate were also tested for fatigue crack growth da/dn according to ASTM E647.

Table 1. Chemical composition for the tested steels.

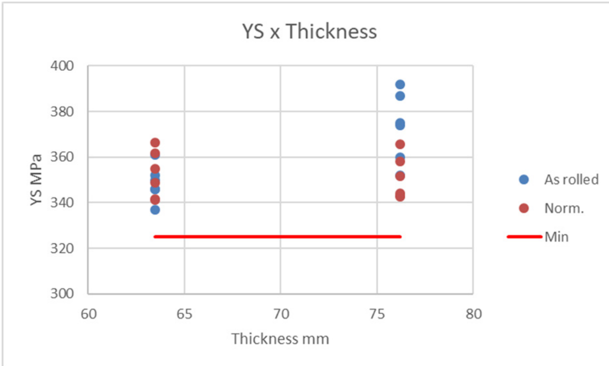
Steel	C%	Mn%	Si%	Al%	Nb%	Ti+V%	N%	Cr+Cu+Ni%
STD+N	0.15	1.45	0.19	0.036	0.035	0.055	0.0039	0.04
HTP+N	0.10	1.15	0.35	0.038	0.065	0.014	0.0053	0.40

A welded joint was produced with samples from the HTP+N steel, with 76 mm thicknes**S**, using the SAW welding process, with an input of 3.9 kJ/mm, 105G PLUS flux and EM12K wire. The microstructural characterization of the welded joint was carried out using scanning electron microscopy using a JEOL microscope, model JEM7100F-LV. The analyzes were made in different regions of the HAZ and in the filler metal. The welded joint was also submitted to tensile tests, bend tests and Charpy with notch located at weld metal, fusion line and 2 mm from the fusion line.

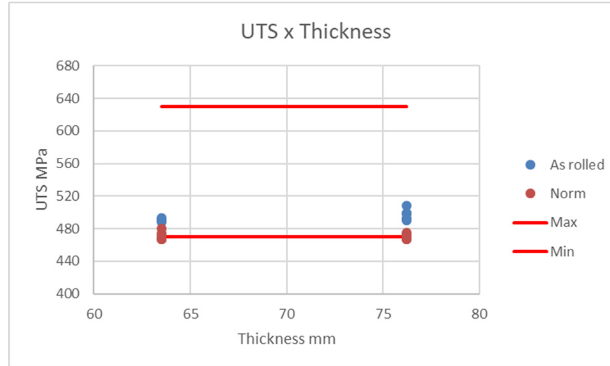
RESULTS

2.1 – Mechanical Testing – Base Metal

All tensile results before simulated normalizing heat treatment met the standard requirements for minimum yield strength (YS) of 325 MPa, minimum ultimate tensile strength (UTS) of 470 MPa and minimum elongation (EL) of 18%, as shown on figure 1. After simulated normalization four UTS results did not meet the 470 MPa minimum requirement, suggesting opportunities to improve the chemical composition and rolling process.



(a)



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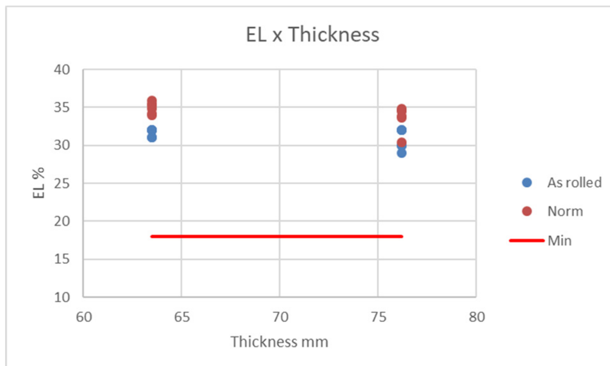
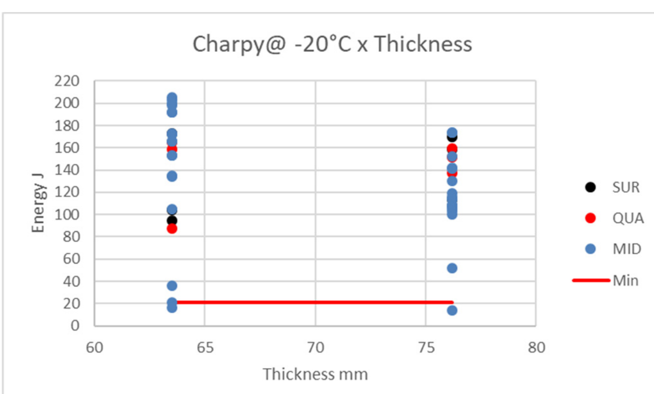


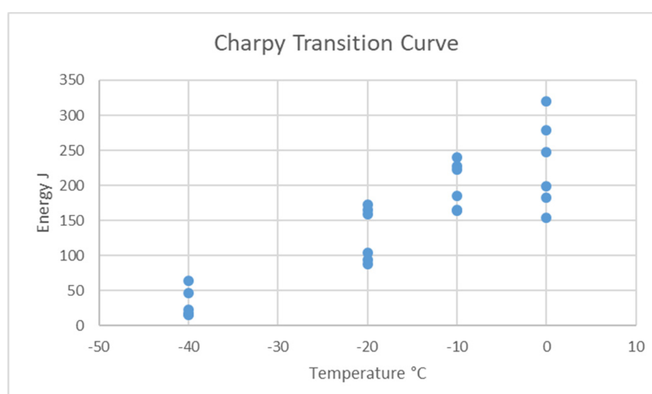
(c)

Figure 1: Tensile test results before (blue circles) and after (red circles) simulated normalization, a) yield strength, b) ultimate tensile strength and c) elongation.

For Charpy, two individual absorbed energy results did not reach the minimum of 21 J at the mid thickness position. This position is unfavorable to toughness due to lower deformation and grain refinement during rolling and the higher segregation intensity of elements such as C, P and S. Optimization of the pass schedule is recommended to improve this result. All standard Charpy results, taken at 2 mm from the surface and tested at -20°C met the mean specification requirement of 27 J and individual of 21 J, as shown in figure 2 (a), along with results for test pieces taken at ¼ thickness. Additionally, a Charpy ductile-brittle transition curve was obtained for test pieces taken from the surface position. As shown on figure 2 (b) the transition temperature was somewhere between -30°C and -40°C.



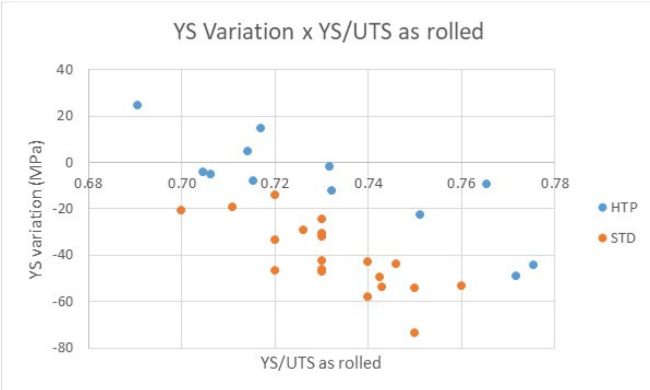
(a)

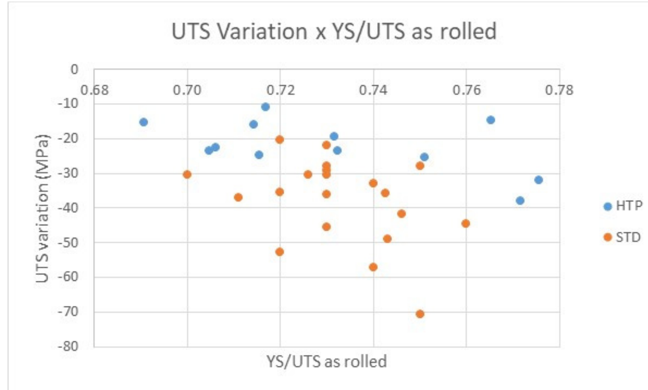


(b)

Figure 2: a) individual absorbed energy results for both gauges in surface, quarter and mid thickness positions. b) individual absorbed energy variation for different temperatures.

Regarding the variation of the tensile results between the as rolled and normalized conditions, the values found in the HTP material proved to be more stable than the conventional alloy (STD). Figures 3a and b show, respectively, the behavior of the YS and UTS variation as a function of the YS/UTS ratio post rolling.





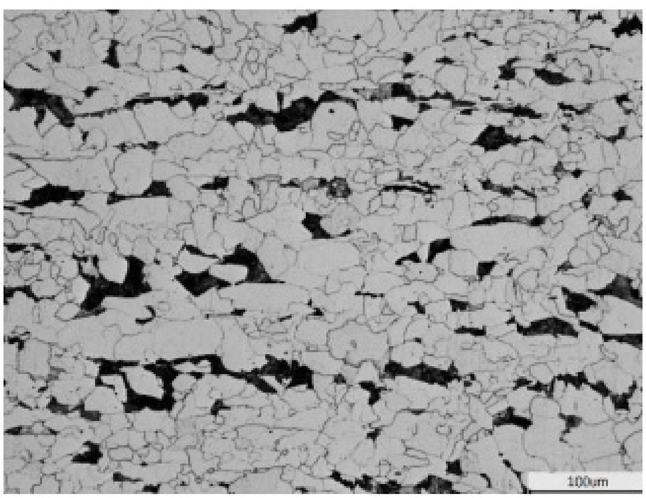
(a) (b)

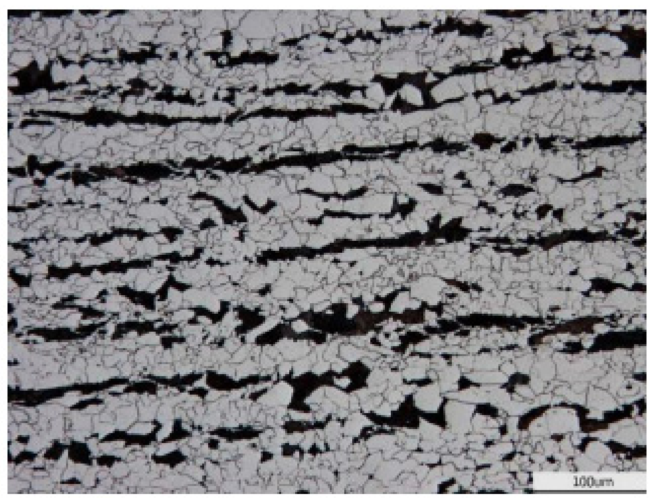
Figure 3: a) Variation between as rolled and normalized YS as a function of the as rolled YS/UTS ratio. b) Variation between as rolled and normalized UTS as a function of the as rolled YS/UTS ratio.

Figure 3 shows that higher YS/UTS ratio in the as rolled condition will provoke higher YS and UTS drops after normalization. Both alloys display the same trend, however the HTP steel has a much lower variation as opposed to the STD steel. This result suggests that the HTP alloy has a more homogeneous and stable microstructure in the as rolled condition, adhering better to the normalizing rolling delivery condition as defined in the European standard.

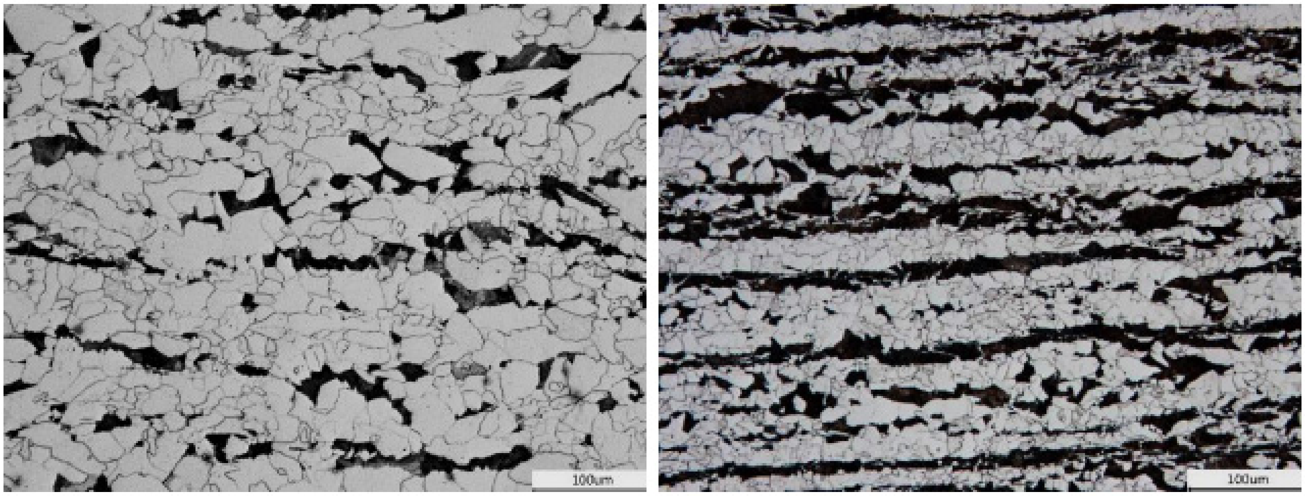
2.2 – Microstructure – Base Metal

Samples from the HTP63 and STD63 steels were taken from the quarter and mid thickness positions for comparison by optical microscopy in the as rolled condition. The microstructures are shown on figures 4 a) to d). Comparisons between the microstructures of the as rolled and normalized conditions of both HTP63 and STD63 are also shown on figures 5 a) to d), representing the quarter thickness position.





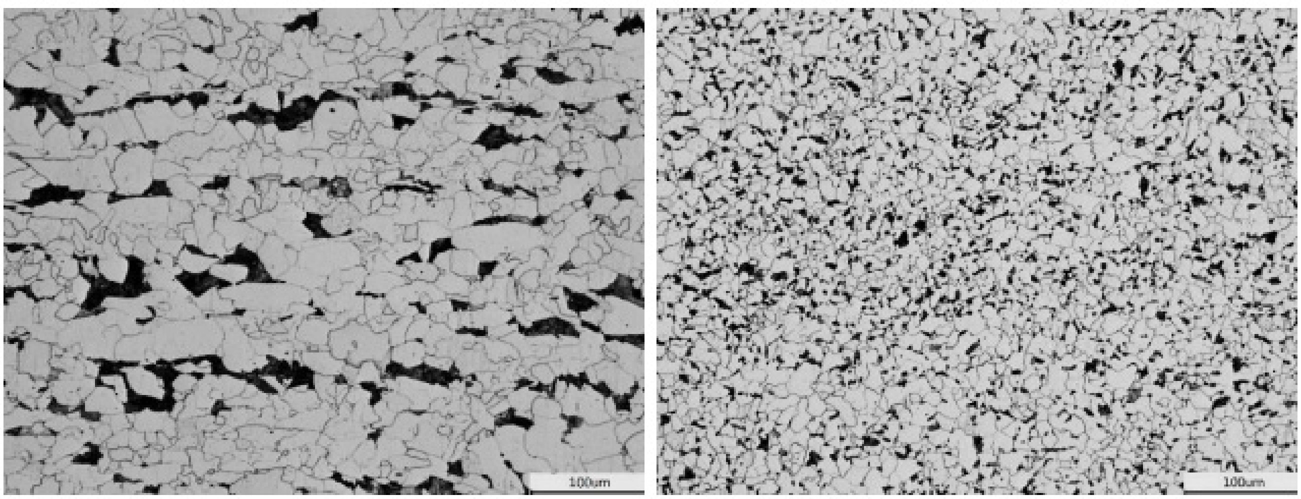
(a) (b)



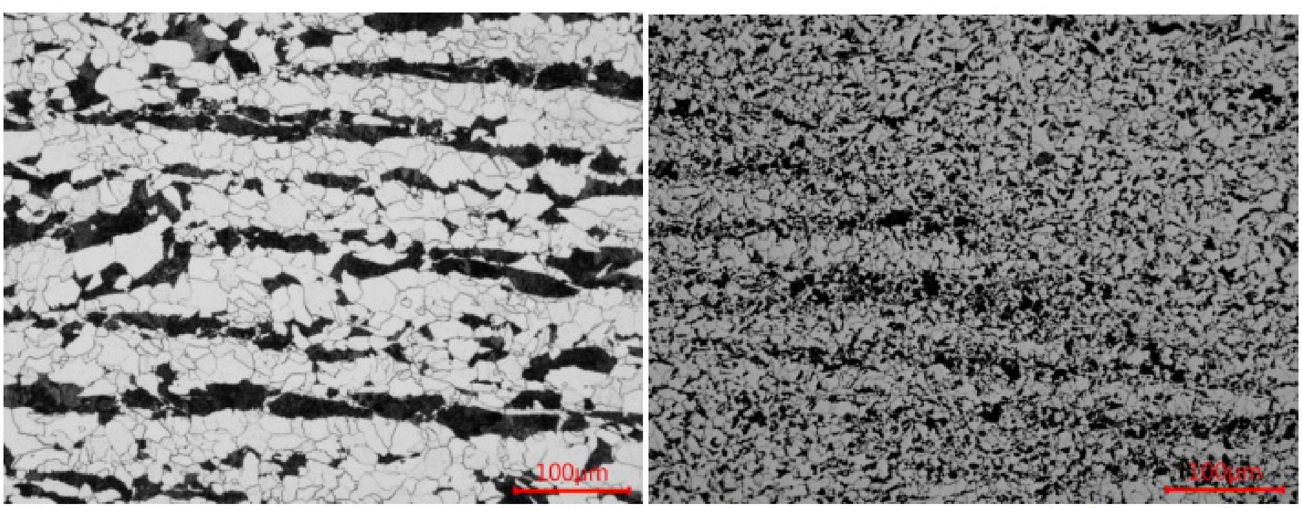
(c) (d)

Figure 4: a) Micrograph of HTP63 steel taken from the quarter thickness position. b) Micrograph of STD63 steel taken from the quarter thickness position. c) Micrograph of HTP63 steel taken from the mid thickness position. d) Micrograph of STD63 steel taken from the mid thickness position.

The micrographs shown on figure 4 clearly indicates the advantage of the HTP alloy in terms of segregation and banding intensity due to the lower content of C and Mn.



(a) (b)



(c) (d)

Figure 5: a) Micrograph of HTP63 steel taken from the quarter thickness position in the as rolled condition. b) Micrograph of HTP63 steel taken from the quarter thickness position after normalization. c) Micrograph of STD63 steel taken from the quarter thickness position in the as rolled condition. d) Micrograph of STD63 steel taken from the quarter thickness position after normalization.

2.3 – Welded Joint Characterization

The welded joint produced a HAZ of approximately 4.2 mm, which can be considered large. This occurred due to the thermal input of 3.9 kJ/mm, a value that generally produces large HAZ. For heavy gauge walls the welding is performed under high heat inputs to increase the efficiency and productivity of the process. These conditions often jeopardize the impact toughness of the welded joint. The observation of the welded joint showed posterior passes produced HAZ over previous passes, forming regions of coarse grains and refined grains in the weld metal, a region called the reheated zone.

Figures 6 shows a micrographic regions in the weld metal (WM). The welding seams are formed by thick layers of columnar structures and the reheated zone is formed by coarse-grained and refined HAZ between the seams. In the refined grained HAZ the heating and cooling process favored the formation of ferrite and pearlite. In the coarse region, grain boundary ferrite (GBF), pearlite, bainite and acicular ferrite are observed. The microstructure of the weld metal, in the columnar grain region, is constituted by acicular ferrite, bainite, pearlite and Widmanstatten ferrite. The microstructural heterogeneity of the weld metal may represent unfavorable mechanical characteristics, such as decreased impact toughness.

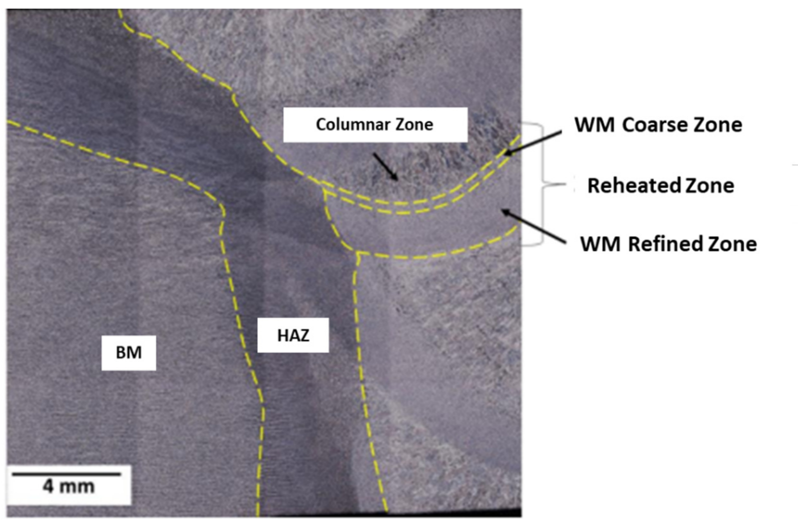


Figure 6: Macrograph of HTP76 welded joint. BM: base metal, HAZ: heat affected zone, WM: weld metal.

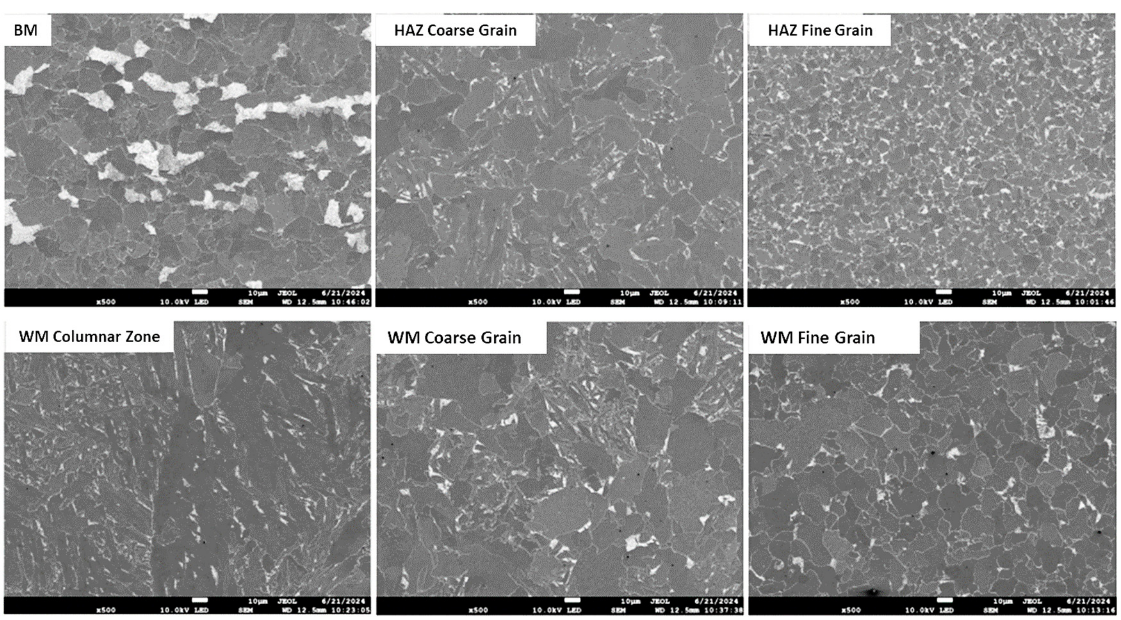


Figure 7: SEM images, showing the microstructural evolution of HAZ and weld metal.

2.4 – Welded Joint Mechanical Properties

Mechanical tests were carried out for the welded joint from of 63 and 76 mm thick plates. For the tensile test, a prismatic test specimen with a rectangular section was prepared, using 100% of the plate thickness and proportional gauge length, as provided by standard EN10025-2. The weld reinforcement was machined so that all faces of the CP were leveled. Under these conditions it was observed that the fracture, both in the 63 mm and 76 mm plates, occurred in the weld metal as shown in Figure 8.

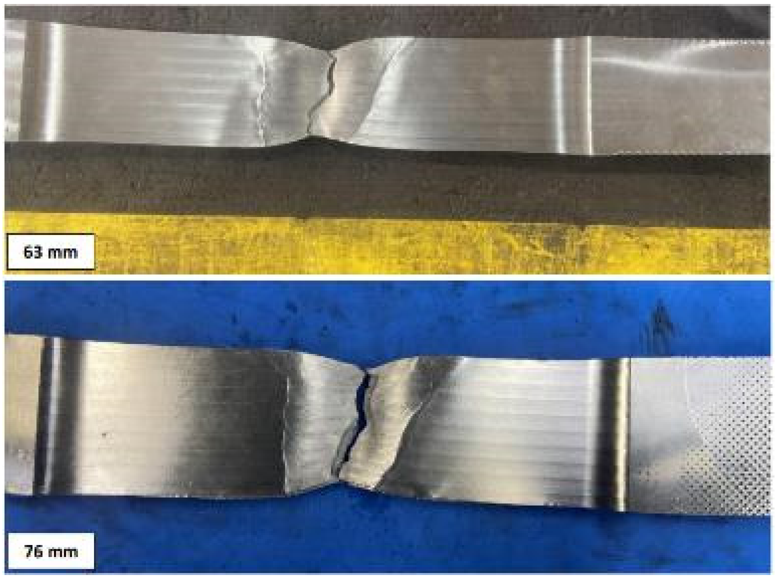


Figure 8: Tensile test pieces from welded joint fractured on weld metal.

The tensile test results are shown on Table 2. These results were approved according to the criteria of the product standard EN10025-2.

Table 2. Tensile results for welded joints

Thickness (mm)	YS (MPa)	UTS (MPa)	EL (%)	YS/UTS
63	408	507	27	0.81
76	386	482	18	0.80

The bending test was carried in a test piece with full thickness of the plate. A cleaver with a diameter of 4x the plate thickness was used, and the bending was done up to an angle of 120°. Figure 9 shows the specimen after bending along with a detail of the weld metal showing that no presence of cracks.

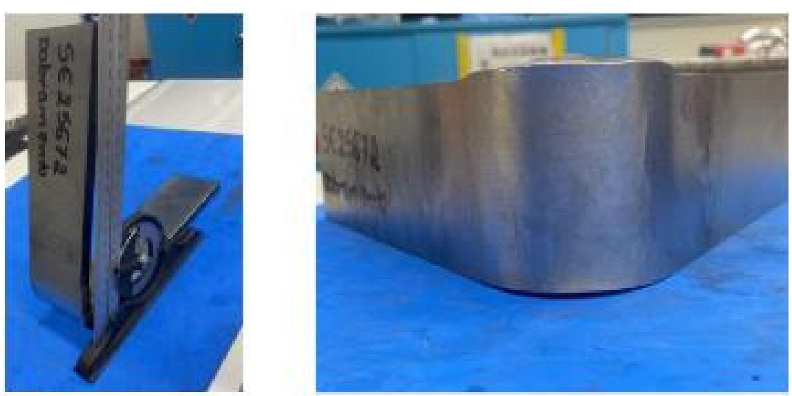


Figure 9: Test piece showing 120° bending angle and absence of cracks.

Charpy impact tests were carried out on different regions of the welded joints: weld metal, fusion line and 2 mm from the fusion zone. Absorbed energy values found are shown in Table 3.

Table 3: Charpy results for welded joints

Position	Temperature °C	Energy 1 (J)	Energy 2 (J)	Energy 3 (J)
Weld Metal		206	58	169
Fusion LIne	-20	36	32	155
Fusion LIne+2mm		381	390	384

The values obtained in the Charpy impact tests were approved by the criteria of EN10025-2 standard. The fusion line, as expected, presented the lowest values of absorbed energy. The toughness displayed by the weld metal is compatible with that verified in the base metal, while the region 2 mm from the fusion line showed significantly higher values than other regions. This region probably coincides with an area of more refined grains.

CONCLUSIONS

All tensile and Charpy results were in conformity with the standard specification. After normalization some UTS results did not meet the minimum specified value, showing that some adjustments must be done in the chemical composition.

Some individual Charpy results did not meet the minimum absorbed energy specification on the mid thickness position of the plate. Improvements shall be made in the furnace temperature and the rolling pass schedule.

Comparison of tensile results before and after simulated normalization in HTP steel and STD steel showed that the first presents greater stability of properties when heat treated. The variation of YS and UTS was smaller in the HTP steel after normalization, independent of the initial YS/UTS ratio, showing greater microstructural homogeneity throughout the plate thickness when compared to the STD steel.

The findings suggest that higher Nb content promoted a more efficient mechanism for suppressing partial recrystallization and thus homogenizing the microstructure.

All mechanical properties evaluated for the welded joint were in conformance with the criteria stablished by the EN10025-2 standard.

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