Influence of the Holding Thickness and Process in the Microstructure and Mechanical Properties of a Microalloyed 380 MPa Structural Steel

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Abstract. Flat low carbon microalloyed structural steels processed by controlled rolling have excellent mechanical properties, particularly regarding toughness, since austenite is rolled with full recrystallization between rolling passes (roughing stage at high temperatures), and, subsequently, with no recrystallization at all between passes (finishing stage at low temperatures), maximizing nucleation of ferrite grains during austenite transformation after hot rolling. However, rolling must be prompted in an intermediate temperature range where recrystallization of austenite between rolling passes occurs partially, as this can lead to great heterogeneity in the grain size distribution of the product, a potential condition to impairs its low temperature toughness. On the other hand, this holding period that is necessary to avoid rolling within this temperature range can last several minutes, reducing the productivity of the rolling line and, in this way, potentially harming the financial performance of the plant. This work was developed to analyze several proposed rolling conditions for the finishing stage during controlled rolling of 16 mm thick strips of a low C Nb-Ti microalloyed steel strip, 380 MPa structural grade, processed in a Steckel mill, to identify the best condition that provides maximum productivity without affecting the required microstructural, toughness and mechanical characteristics of the final product.

Introduction

One of the main restrictions to the manufacture of flat products through the controlled rolling of microalloyed steels is the need to interrupt the process over a certain temperature range (i.e., the observance of the so-called holding period between the roughing and finishing stages). In this region recrystallization of austenite between rolling passes tends to be partial, which increases the heterogeneity of its grain size distribution and tends to degrade the toughness of the final product. This temperature range lies between the so-called Recrystallization Limit Temperature - RLT (minimum temperature where at least 80% of recrystallization occurs in the interval between two consecutive passes) and the Recrystallization Stop Temperature - RST (maximum temperature where a maximum of 20% of recrystallization occurs in the interval between two consecutive passes). Depending on the specific rolling process conditions adopted, this holding period can last some minutes, significantly affecting the productivity of the mill and generating considerable temperature gradients through the thickness of the rolling stock, which can also affect its mechanical properties.

The aim of this work was to optimize the holding stage during controlled rolling of 16 mm thick strips of a low C Nb-Ti microalloyed steel, 380 MPa structural grade, processed in a Steckel mill, in order to minimize the productivity loss while keeping the performance of the final product. So, new rolling schedules for the finishing stage of TMCP were assessed, mainly varying the strip thickness at the holding stage.

Material and Experimental Techniques

The steel chosen for this experiment was a 380 MPa structural grade, microalloyed with Nb and Ti, with the following chemical composition range: 0.12 wt. % C_{max}, 1.20% wt. Mn_{max} and 0.010 up to 0.22 wt. % Nb+Ti+V. The aimed mechanical properties were specified by the Brazilian Standard NBR 6656 - Grade LNE380-J2 as follows: Yield Strength, 380-530 MPa; Tensile Strength, 460-600 MPa, Elongation, 23% minimum; Charpy Energy, 27 J @ -20°C minimum [1].The dissolution temperature range of the niobium carbonitrides was between 1170°C and 1185°C according to Irvine [2], slightly lower than the usual slab discharge temperature used for this kind of steel. Slabs with 250 mm thickness were controlled rolled in the austenitic field; the 16 mm strips were cooled in the run-out table and coiled at the same aimed temperature. The different conditions of finishing stage of TMCP adopted here are described as follows, respectively with respect to start strip thickness and number of passes applied during finishing stage:

- #0: no formal holding stage;
- #1: 30 mm; one pass;
- #2: 30 mm; two passes;
- #3: 50 mm; three passes.

In the #0 condition, with no holding stage, dynamic rolling speed control was adopted for the finishing stage to make strip reach specified finishing temperature range.

After coil cooling, samples were extracted from the tail of the strips to determine their microstructure and mechanical properties. Specimens were submitted to metallographical analysis using optical microscopy and a complete EBSD characterization was conducted. Specimens were machined in the transversal direction of the rolled strips for tensile testing according to the ABNT Standard NBR 6673 [3] and Vickers hardness measurement. Toughness was measured through the determination of DBTT curves, under temperature range from -100°C to +20° at intervals of 20°C. DWTT tests were also performed at -20°C, but only for informative purposes.

Austenite conditioning and microstructural evolution during rolling were simulated for all cases using MicroSim® model. Results from this software, specifically austenite mean grain size, its accumulated strain and soluble niobium at the end of rolling, as well the precise temperature evolution of the strips in the run-out table, supplied by the Level II of the Steckel Mill line, were used for the calculation of the austenite transformation and Ar_3 temperature of the strips by the PhasTransSim® model [4].

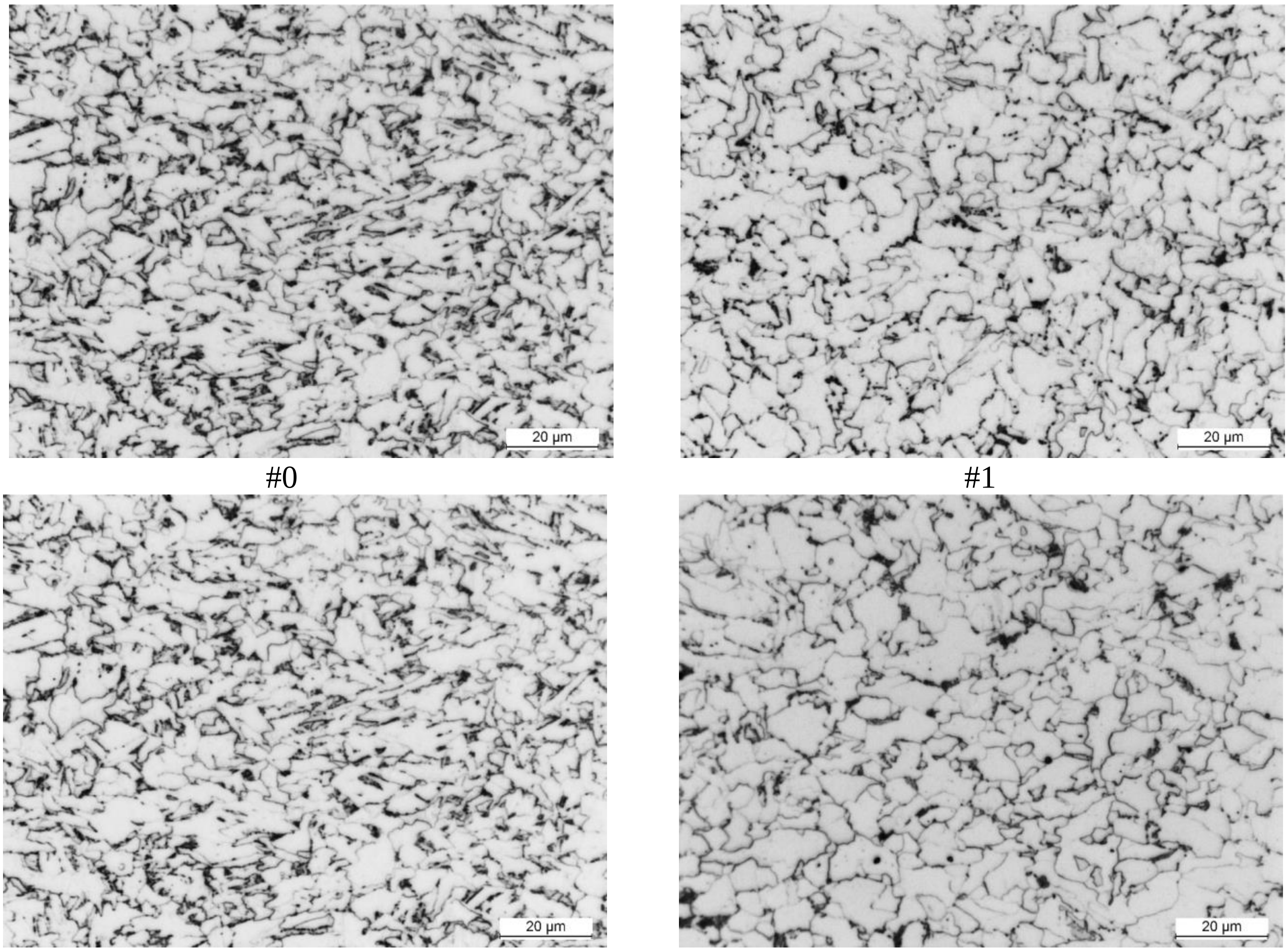
Results and Discussion

Mechanical Properties. Table 1 shows the mechanical properties determined from the strips rolled according to the different TMCP finishing stage conditions. All of them satisfied the requirements imposed by NBR 6656–Grade LNE 380-J2. The #0 sample showed the highest levels of mechanical strength; the same occurred with toughness, regarding ITT@27J and DWTT, but not with CVN. However, the difference between the values got in the Charpy tests in this work was negligible: 16 J (4%) maximum. The #3 sample showed the minimum values of mechanical strength, but maximum ductility, minimum yield ratio and fair toughness. These last features are favorable if the strip is to be cold formed at the customer, especially regarding springback trend; however, its yield strength is too near the minimum value specified by LNE 380. The values of the ratio between soluble Nb at end of rolling, calculated by the PhasTransSim model, and nominal Nb amount in the steel were 47%, 51%, 53% and 39%, respectively for strips #0, #1, #2 and #3. In fact, the #3 strip showed the minimum value in this sequence, which can explain its lower strength.

Microstructural Analysis. Figure 1 shows the ferritic-pearlitic microstructure of the strips studied in this work observed at the optical microscope. The comparison of these micrographs suggests that grain size of the #0 is the finest. The amounts of pearlite in these microstructures were very low, as determined by manual point count: 0.4%, 1.8%, 1.1% and 2.3%, respectively for #0 , #1, #2 and #3 strips.

Table 1: Mechanical properties measured from the strips studied in this work. YS: Yield Strength; TS: Tensile Strength; YR: Yield Ratio; El: Elongation; HV: Vickers Hardness; CVN: Energy Absorbed during Charpy Test at -20°C; ITT@27J: Impact Transition Temperature at 27 J; DWTT: Ductile Area Fraction at -20°C measured by Drop Weight Test.

Designation	YS [MPa]	TS [MPa]	YR [%]	El [%]	HV	CVN [J]	ITT@27J [°C]	DWTT [%]
#0	474	547	87	28	175	391	-96	85
#1	430	507	85	30	163	407	-78	20
#2	442	523	84	30	170	399	-56	27
#3	392	475	82	32	150	396	-77	41



#0 #1 #2 #3

Figure 1: Optical micrographs of the strips studied in this experience, nital etch.

Table 2 shows the quantitative microstructural parameters determined using EBSD, measured at ¼ and ½ thickness of the strip. Grain sizes were measured considering 4° and 15° misorientations, as the first case is more representative to correlations with mechanical strength, and the latter with toughness. Grain sizes determined at ¼ and ½ thickness showed similar values; so, it can be presumed that slab central segregation was light and strain penetration across thickness during hot rolling was satisfactory. The so-called Kernel parameter express dislocation density in microstructure.

Correlations between Mechanical Properties and Microstructure. Figure 2 shows relationships between mechanical strength and grain size plus kernel, as measured by EBSD. Grain size in these graphics were measured considering a 4° misorientation, as this condition corresponds to the microstructural size unit that controls strength. As already expected, strips with grain size more refined and with higher dislocation density showed higher mechanical strength and lower ductility.

Table 2: Quantitative microstructural parameters determined by EBSD analysis.

Designation	¼ Thickness			½ Thickness		
	Grain Size [µm]		Kernel [°]	Grain Size [µm]		Kernel [°]
	4°	15°		4°	15°	
#0	3.4	4.1	1.1	3.4	4.2	1.2
#1	4.2	4.7	0.9	4.1	4.7	1.0
#2	4.3	4.9	0.9	4.3	5.0	1.0
#3	4.5	5.1	0.8	3.9	4.4	0.9

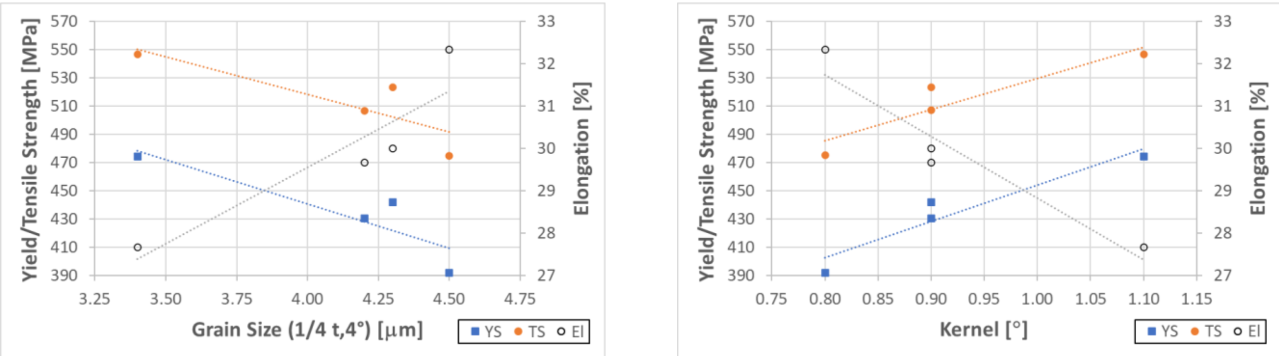


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Figure 2: Correlation between tensile mechanical properties and (a) grain size measured considering misorientation of 4° and (b) Kernel at ¼ thickness of the strip.

Figure 3 shows the calculated contributions of each strengthening mechanism that operates in this kind of steel, which is: solid solution, grain size, dislocation density and precipitation. It can be seen that the contribution of grain size is predominant. The prediction of yield strength was reasonable for most of the strips. It can be seen that no contribution of fine precipitation strengthening was calculated for the case of #3 strip, a fact which is compatible with the lowest value of soluble Nb in the end of rolling calculated by MicroSim, as already mentioned.

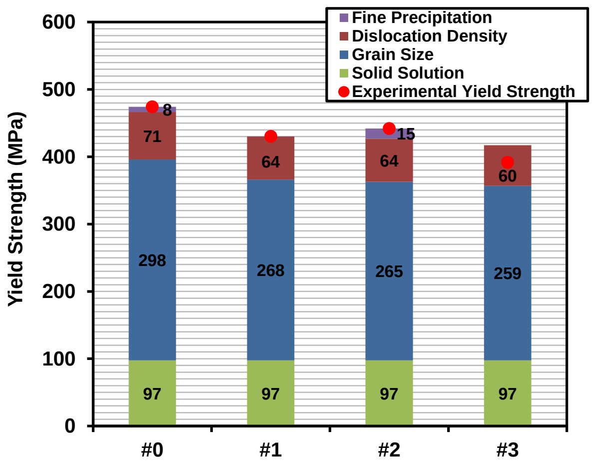
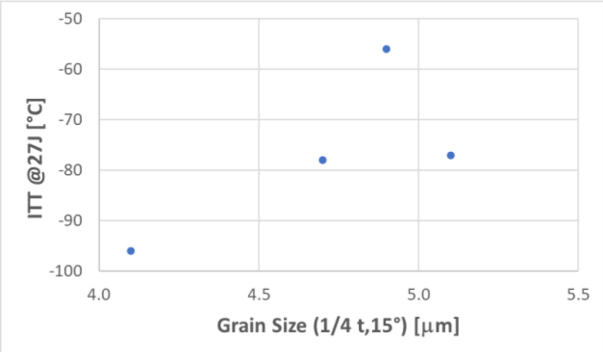


Figure 3: Calculated contributions of several strengthening mechanisms to the yield strength of the strips studied in this work.

Figures 4(a) and (b) show the correlation between toughness, expressed as impact transition temperature at 27 J as measured by the Charpy test and ductile fracture fraction as measured by DWTT, with grain size, measured respectively at ¼ thickness and at ½ thickness. In this specific case both grain sizes were measured by EBSD considering 15° misorientation, which controls toughness; the grain size at ½ thickness was chosen for correlation with DWTT results because its specimen includes the full thickness of the strip and, of course, its core, where segregation is maximum. One can see in this figure that the effect of grain size was not so evident in the case of ITT@27J but was confirmed with the DWTT results.



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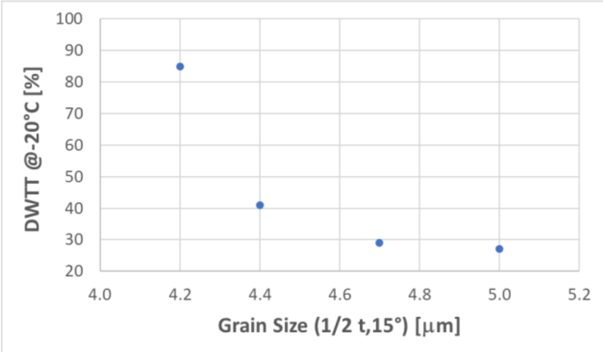

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Figure 4: Correlation between grain size and (a) impact transition temperature at 27 J measured by Charpy tests and (b) ductile fraction in fracture area measured by DWTT observed in the strips studied in this work.

Correlations between Mechanical Properties, Microstructure and Rolling Process. Figure 5(a) shows that mean ferritic grain size increased with strain applied in the finishing stage of TMCP. At first this was surprising. Recrystallization of austenite is negligible during finishing, so strain hardening is proportional to thickness reduction applied in this stage which, theoretically, promotes a quicker formation of more refined ferrite. However, this was not observed in this work, as figure 5(b) shows that the measured mean ferrite grain size *increased* with austenite accumulated strain calculated by the MicroSim model.

Figure 5(c) can explain such behavior, as it shows the measured mean ferritic grain size increased with the Ar_3 temperature calculated by the PhasTransSim model. As strain hardening increases Ar_3 [5], as effectively shown in Figure 5(d), formation of ferrite starts at a higher temperature, which contributes to increase its size. So, the finishing strategy #0 using speed control was more effective to refine the final microstructure, improving mechanical strength and toughness.

Productivity. As expected, higher holding thicknesses and number of passes during finishing rolling increased total rolling time and decreased the productivity of the Steckel Mill Line. The relative relationship between total rolling times was 100:100:120:136, respectively for #0, #1, #2 and #3 strips. So, considering adequation to the LNE380 standard and productivity, may be case #1 is the best, as rolling line productivity is not impaired, the mechanical properties specifications of the standard are fully satisfied and mechanical strength and yield ratio are not so high, which favors cold forming operations at the customer.

Summary

Several finishing rolling approaches for TMCP were assessed in this study regarding the production of a 16 mm strip of structural Nb-Ti steel with minimum yield strength of 380 MPa rolled at a Steckel mill. Although all finishing conditions proposed here allowed to achieve a product that met the specified levels of mechanical strength and toughness, it was found that the increase of the holding thickness led, predictably, to an increase in the total rolling time, but also to an increase in the grain size the final product, with the consequent reduction in the magnitudes of strength and toughness. This was attributed to the increase in the strain hardening austenite at the end of rolling, which led to an increase in the Ar_3 temperature and to the formation of ferrite under higher temperatures, which contributed to the increase its grain size.

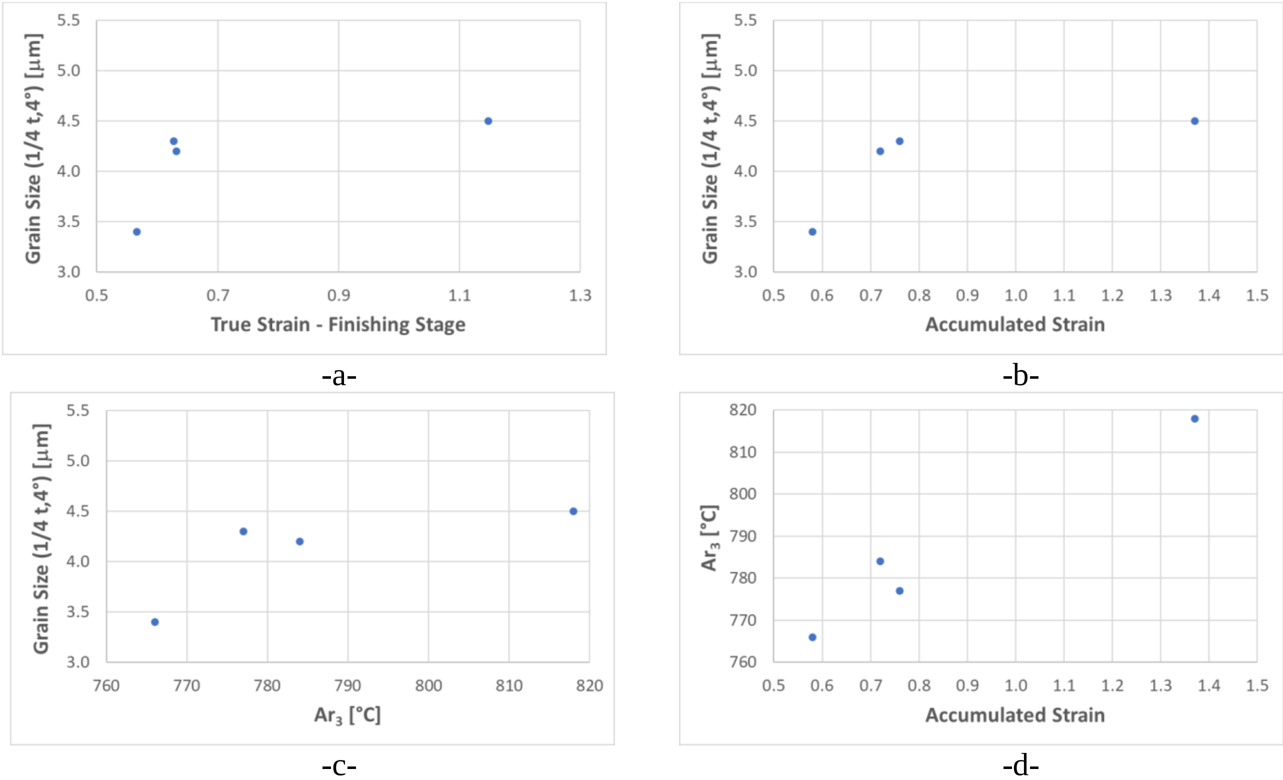

Figure 5: Measured mean ferritic grain size at ¼ thickness in function of the evolution of (a) true strain in the TMCP finishing stage, (b) accumulated strain of austenite immediately after TMCP, calculated by the MicroSim model, and (c) Ar_3 temperature as calculated by the PhasTransSim model. Ar_3 temperatures in function of accumulated strain at rolling end as calculated by MicroSim are shown in (d).

Acknowledgements

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