RECENT DEVELOPMENTS ON CONTROLLED ROLLING TECHNOLOGY AT COMPANHIA SIDERÚRGICA PAULISTA - COSIPA[1]

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- INTRODUCTION

Companhia Siderúrgica Paulista - COSIPA, an integrated Brazilian steelworks, produces 3.9 Mt of steel per year. In 1996, about 1.05 Mt of plates were delivered; 12% of this amount were microalloyed steels, processed through controlled rolling. Since its commissioning in 1978, this plate mill produced approximately 15.2 Mt of plates. Figure 1 shows a picture of the rolling stand.

The development of controlled rolling at COSIPA began in the late seventies. Since 1983, high performance plates according to the standards API 5L-X65 and X70 were routinely produced. The grade X80 was fully developed in 1987. During the nineties, however, the development emphasis of controlled rolling processes concentrated on the enhancement in the productivity of this process and in the increase of the plates' properties consistency.

COSIPA's plate mill consists of a single stand four-high reversing mill. As the operations of roughing and finishing rolling are executed in the same stand, the output of the mill is considerably limited. This is due to the holding time between the roughing and finishing steps that has to be introduced in order to carry out the last step in the temperature range where austenite does not recrystallize anymore.

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Two options were adopted at COSIPA in order to decrease this holding time. In the case of single plates, the use of Intermediate Forced Cooling (IFC) proved to be successful. This solution was very opportune, as this system was already available at the plate mill. For its turn, for bulky batches of the same kind of product, tandem rolling is more effective to increase the productivity of the mill. A work for the determination of the optimised thickness of the rolling stock in the holding step, maximising the number of plates being simultaneously processed, was also developed.

Figure 1: Picture of COSIPA's 4100 mm plate mill.

Another feature to be considered is the promising market for narrow controlled rolled plates. However, its production in the plate mill is economically feasible only when using the so-called double or triple width plates. That is, the rolling stock produced in the plate mill has the double or triple of the final skelp, which is got through longitudinal cutting of the original rolling stock.

- INTERMEDIATE FORCED COOLING

There is no doubt that the use of forced cooling during the holding step of controlled rolling would shorten this idle time. However, there was some concern about the influence of this new process over the final properties of the plate. An excessively severe cooling can result in a pronounced temperature gradient along plate thickness. In this case, its surface would be over-cooled during the application of the water sprays. After the cooling process, the surface would be submitted to a recalescence, as heat would flow from plate core. This thermal cycle can lead to excessive precipitation, affecting significantly the ferrite start temperature and austenite recrystallization kinetics, resulting in the formation of elongated and deformed superficial grains. These alterations in the microstructure of the plate surface would not change significantly its overall properties, but could induce tensile residual stresses in its surface, which could produce surface cracks depending on their magnitude. This "chilled" superficial microstructure can also, in some cases, increase the transition temperature determined by Charpy impact tests.

A previous investigation work was developed, using a laboratory rolling mill to simulate the controlled rolling of a Nb-Cr steel, normally used for the production of API 5L-X52 plates. The application of cooling rates from 1.1 to 3.5^{o}C/s during the holding step did not produce statistically significant differences in the microestructure, mechanical strength and toughness of the final product.

These promising results encouraged the execution of industrial trials with Cr-Cu, Nb-Cr and Nb-Ni-Cr steels. During the holding step of controlled rolling, one or more cooling passes were applied to the rolling stock, in function of its temperature in the end of the roughing step, thickness and width. The plant IFC facility was used with 100% of its capacity, that is, 10,000 l/min at 3 kgf/cm^2.

The results of these industrial scale experiments also showed no significant changes in mechanical properties and microstructural characteristics when IFC was introduced. Cooling rates employed in the IFC experiments ranged between 3.5 and 5.0^{o}C/s. The final product showed good planicity. Besides that, IFC practice did not introduce any significant change in hot rolling load magnitudes at the finishing passes.

After these trials, the IFC process was routinely used for microalloyed shipbuilding plates. Further monitoring studies showed that the holding step time was reduced by almost 50% for light plates and 20% for heavy plates; total processing time reduction was about 18% and 8%, respectively, as can be seen in Figure 2. However, real operational results were even better: considering the dimensional specific mix of shipbuilding plates produced at COSIPA, a 22% increase in the overall controlled rolling productivity was effectively achieved.

After some years of experience, the IFC process was extended to plates produced according to the API 5L X60/X65 standards. Once more, the productivity of the process was enhanced, without any undesired effect in the properties of the final product.

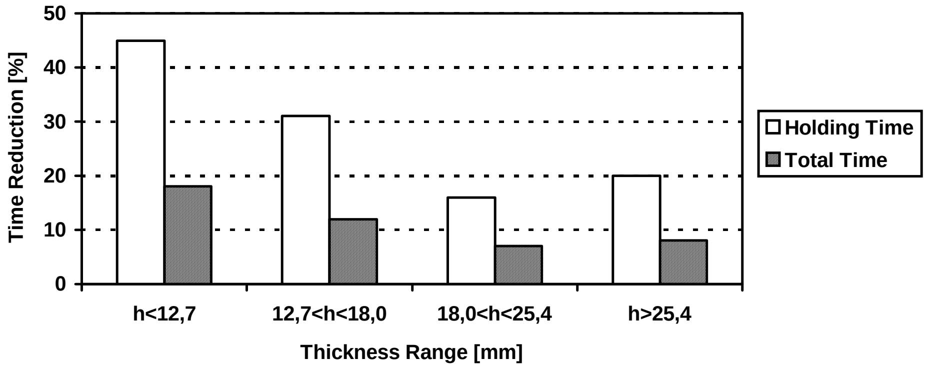

Figure 2: Reduction in the holding step time and in the total processing time associated with the use of the IFC process during the controlled rolling.

- OPTIMIZATION OF THE THICKNESS OF ROLLING STOCK IN THE HOLDING STEP

The determination of the rolling stock thickness during the holding step of controlled rolling is of utmost importance. Metallurgically speaking, any alteration in this parameter implies in a change in the total strain distribution between the roughing and finishing steps. When this intermediate thickness is increased, strain applied during the roughing step is decreased, with a corresponding increase of strain applied in the finishing step.

A greater strain degree applied in the non-recrystallization range of austenite, that is, during the finishing step, will obviously reflect in a more strain hardened structure after rolling. So, this final austenitic structure will be more refined, as it will have a greater amount of grain/sub-grain boundaries available for the posterior transformation of austenite to ferrite. This structure will have a minimised grain size if the strain degree applied during the roughing step is equal or greater than 60%. In this case, microstructure after the roughing step will be constituted of recrystallized austenite with minimum grain size.

The effect of a greater intermediate rolling stock thickness over mechanical properties is not so clear. In principle, the more refined microstructure would lead to a simultaneous increase in mechanical resistance and toughness. However, other microstructural effects, like alterations in the morphology of the constituents and decrease in the precipitation hardening potential in ferrite can lead to unexpected results. So, any alteration of this process parameter must be cautiously done: a previous analysis about its possible effects for each kind of microalloyed steel is strongly recommended.

From the point of view of productivity, the increase of intermediate thickness means shorter rolling stocks during the delay between roughing and finishing steps. Hence, a greater number of rolling stocks can be simultaneously processed using tandem rolling. However, cooling time necessary for these heavier rolling stocks to reach the ideal start temperature for the finishing step can be excessive, as its roughing step ends earlier (i.e., temperature at the end of the roughing step is higher) and, as they are thicker, their cooling rates are significantly lower than thinner intermediate rolling stocks. So, there is an optimum intermediate stock thickness, which balances these contradictory tendencies and allows maximum productivity during controlled rolling.

The quest for a more efficient controlled rolling process with consistent quality products motivated the development of a research project to determine the effect of intermediate rolling stock thickness over the mechanical properties of the product and the productivity of controlled rolling process. A Nb-Ti microalloyed steel, suitable for the production of shipbuilding plates according to the DH-32 standard, was chosen for these experiments. Plates with final thickness (**t_f**) of 12.7, 25.4 and 32.0 mm were submitted to controlled rolling using different intermediate rolling stock thickness (**t_i**), as shown in Table I. Slab thickness was the same for all plates studied. For the sake of simplicity, the intermediate rolling stock thickness values were multiples of the final product thickness values.

Final Thickness **t_f** [mm]	Intermediate Rolling Stock Thickness **t_i** [mm]			
	2 t_f	**3 tf**	**4 tf**	**5 tf**
12.7	25.4	38.1	50.8	63.5
25.4	50.8	77.1	101.6	
32.0	64.0	96.0		

Table I: Intermediate rolling stock thickness values used in the experiment.

A statistical analysis between the mechanical properties determined from plates produced using different values of intermediate rolling stock thickness can be seen in Table II. This comparison was carried out using Variance Analysis (ANOVA) for the 12,7 and 25,4 mm, while the Student Test was used for the 32,0 mm plate, as plates with this thickness were tested using only two values of intermediate rolling stock thickness.

The results of Table II show that the variation in the intermediate rolling stock thickness did not affect the 12.7 mm plate. However, as final product thickness increases, the effect of that rolling parameter must not be neglected. For the 25.4 mm plate, yield strength was somewhat influenced by intermediate rolling stock thickness, increasing from 380 to 395 MPa as $\mathbf{t_i}$ was changed from 50.8 to 77.1 mm (2 to 3 $\mathbf{t_f}$). In the case of the 32.0 mm plate, all properties but total elongation were affected by the alteration on the intermediate rolling stock thickness from 64 to 96 mm (2 to 3 $\mathbf{t_f}$), as can be seen in Table III. These findings show that the effect of the intermediate rolling stock thickness is more significant for heavy plates. Considering mechanical strength, this effect was more explicit for yield than for tensile strength, as can be seen by the evolution in the yield ratio values.

	Yield Strength	Tensile Strength	Yield Ratio	Total Elongation	Charpy Energy at -20°C
ANOVA $\mathbf{t_f}$ = 12.7 mm	EQUAL 58,7%	EQUAL 47,5%	EQUAL 60,1%	EQUAL 38,8%	EQUAL 12,4%
ANOVA $\mathbf{t_f}$ = 25.4 mm	DIFFERENT 98,3%	EQUAL 92,4%	EQUAL 50,2%	EQUAL 71,2%	EQUAL 22,2%
STUDENT $\mathbf{t_f}$ = 32.0 mm	DIFFERENT 99,4%	DIFFERENT 99,9%	DIFFERENT 98,9%	EQUAL 83,6%	DIFFERENT 98,9%

Table II: Results of statistical analysis from mechanical properties determined from plates processed by controlled rolling with different values of intermediate rolling stock thickness, considering each value of final thickness. Confidence level adopted: 95%.

These results lead to the conclusion that, as total deformation (slab → plate) increases, the effect of the intermediate rolling stock thickness is reduced. That is, the distribution of strain between the roughing and finishing steps does not influence the product properties above a certain grade of total deformation. This conclusion is confirmed by the decreasing values of confidence degree produced by the Student and ANOVA tests as the thickness of the final plate is reduced.

	Yield Strength [MPa]	Tensile Strength [MPa]	Yield Ratio [%]	Total Elongation [%]	Charpy Energy at -20°C [J]
$\mathbf{t_i}$ = 64 mm (2 $\mathbf{t_f}$)	360	495	73	30	110
$\mathbf{t_i}$ = 96 mm (3 $\mathbf{t_f}$)	400	505	79	29	150

Table III: Alteration in the mechanical properties of plates in function of the intermediate rolling stock thickness values.

So, at least for plates with thickness equal or less than 25.4 mm, the alteration in the intermediate rolling stock thickness does not lead to significant alterations in the mechanical properties of final plate. So, the value of this parameter can be chosen only regarding the most favourable condition to maximise plate mill productivity through the use of a optimised tandem rolling scheme. In the case of heavier plates, the use of a thicker intermediate rolling stock must be done with care; in this case, C and Mn contents of the steel were judiciously reduced to balance mechanical properties. These reduction in the plate alloy content leads to additional benefits, as a slight economy in the consumption of ferro-alloys and some improvement in the product weldability.

This study made feasible the use of optimised values of intermediate rolling stock thickness according to the specific dimensions (thickness and width) of final plate, leading to a 21% increase of the overall productivity of the plate mill during the controlled rolling process.

- PRODUCTION OF TRIPLE WIDTH PLATES

The Brazilian demand for API linepipes with relative small diameter (300 to 500 mm) is becoming stronger. Skelp used to forming these tubes must be narrow, that is, its width range varies from 950 to 1,600 mm. The use of plate rolling to make this skelp is unfeasible, as these width values make their production economically unfeasible; normally this application requires material produced in hot strip mills.

There is a chance to produce such skelp in plate mills using "multi-width" plates; that is, the width of the rolling stock processed in the mill is a multiple (double or triple) of the final product width. After rolling, the plate is longitudinally cut and two or three skelps with the requested width are got.

However, there are some metallurgical questions to be previously answered before routinely using this processing route. Normally plates are produced from continuously cast slabs, whose solidification process produces segregation of some elements normally present in steel, mainly C, Mn, P and S, which concentrate in the middle portion of the slab. This segregation is inherited by the subsequent plate. So, in a double width plate, the longitudinal cut will be done exactly in the maximum segregation region. The higher C and Mn content in this portion of the skelp can be potentially harmful to the longitudinal welding process used to make the pipes, as steel with increased equivalent carbon is more prone to cracking and other welding problems. Another problem to be considered is the difference of plate crown values between the middle and the border of the skelp. In the case of triple width plates, these problems are somewhat less critical, as the longitudinal cuts did not coincide with the most critical region in terms of segregation and maximum plate crown.

No literature references were found about metallurgical characterisation of double or triple width plates. This fact motivated the development of a research project at COSIPA with the objective to characterise quantitatively chemical segregation, microstructure and mechanical properties differences between skelps extracted from triple width plates, in order to check product consistency.

The material studied in this project was an API 5L X-60, Nb-Ti microalloyed steel. The mother plate had width of 3000 mm; it was cut longitudinally, yielding three skelps with width equal to 980 mm. About 126 skelps, produced from 42 plates, were analysed in terms of chemical composition (C, Mn, Si, P, S, Nb, Ti, Al and Ca), microstructure (global, ferritic and perlitic grain size, pearlite volumetric fraction and ferritic mean free path) and mechanical properties (yield and tensile strength, yield ratio, 5 kg Vickers hardness and energy absorbed during Charpy impact test carried out at -40, -30, -20, -10, 0 and +10^{o}C).

The results of the Variance Analysis (ANOVA) and Test of Means (Student) revealed that no significant statistical differences were observed in the studied skelps, considering all metallurgical parameters determined here. All skelps satisfied the requirements of the API 5L-X60 standard and performed very well at the customer.

Hence, the use of this production route was approved, as it does not imply in quality restrictions in the product. Besides that, the use of triple width plates multiplied the productivity of the plate mill by 2.5 fold and increased metallic yield by 1.6% in relation to the traditional processing route of single width plates. These results make the use of plate mill feasible for this narrow product.

- FURTHER ACHIEVEMENTS

The development of projects for optimising and improving controlled rolling processes at COSIPA’s plate mill is permanent. At this moment, work is being conducted to test new alloy designs and thermomechanical treatments not only to improve productivity, but also to ease the execution of the controlled rolling process, maximising the consistency of properties in the final product. After all, it is not enough only to produce high quality products; they must be produced in a consistent, reliable and economical way.