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Development of alternative as-rolled alloys to replace quenched and tempered steels with tensile strength in the range of 600–800 MPa

Antonio Augusto Gorni [a], Paulo Roberto Mei [b,*]

[a] Companhia Siderúrgica Paulista, Estrada de Piaçagüera km 6, 11573-970 Cubatão, SP, Brazil
[b] Faculdade de Engenharia Mecânica, Universidade Estadual de Campinas–UNICAMP, 13083-970 Campinas, SP, Brazil

Abstract

The fierce competition between steelworks and different alloy design approaches are the motivation behind the development of new microalloyed structural steels which must satisfy increasingly severe mechanical strength and toughness requirements. Other equally desirable aspects for these new materials are the suppression of heat treatments after hot rolling and better weldability, which makes this alloy evolution even more complex. As weldability improvement requires minimization of the carbon content of the steel, these new steels must present hardening mechanisms which does not require the presence of this element. Up to this moment, the most feasible answers to this challenge are steels hardened by copper precipitation, like HSLA-80 or ASTM A710, and the so-called ultra low carbon bainite (ULCB) steels. The aim of this work was to study the effects of some controlled rolling parameters over the mechanical properties of these relatively new steels. The knowledge of these effects certainly will help in the definition of optimised process conditions for these new steel alloy designs. It was verified here that the total strain applied during hot rolling and the finishing temperature were essential to improve the toughness of both alloys; the effect of the former parameter revealed to be more important. The aged HSLA-80 steel showed greater values of yield strength, but lower toughness than the as-rolled ULCB alloy. This fact is certainly due to the aging treatment that is normally applied to the first alloy.

Keywords: Microalloyed steels; Copper precipitation

1. Introduction

The remarkable development of microalloyed steels, particularly for structural, shipbuilding and pipe applications, is due to the good toughness characteristics of these materials, allied to relatively high levels of mechanical strength. Besides that, their cost is lower than equivalent heat-treated alloys, as the characteristics of microalloyed steels are achieved directly from the rolling heat. As a matter of fact, controlled rolling revealed to be an essential thermomechanical treatment to make such properties combination feasible in Nb, Ti and/or V microalloyed ferritic-perlitic steels. Some examples of products made with such alloys are plates for the manufacturing of pipes according to the API X-60, X70 and X80 standards, since their wall thickness are below 20 mm.

However, heavier plates with this same strength and toughness level, or stronger and tougher light plates, require the use of more complex microalloyed alloys. Some examples of application of such products are plates for offshore platforms, valves and fittings for pipelines, parts for military vehicles and off-road trucks, equipments for oil wells and structural components for war ships [1–5]. Besides this balanced mechanical characteristics, this kind of material must be easily processed by the customer. This includes good weldability, even for heavy plates, with a thickness range between 25 and 100 mm.

Two alloy concepts were proposed to fulfill these stringent requirements: microalloyed steels hardened by copper precipitation (ASTM A710/HSLA-80) [6] or through the formation of a tough bainitic microstructure (ULCB–“ultra low carbon bainite”) [7]. These steels were originally developed to be used as pipes and pipeline fittings. One of the great advantages of these alloys is that they do not need to be submitted to a quench and temper heat treatment in order to get

* Corresponding author.
E-mail address: pmei@fem.unicamp.br (P.R. Mei).

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their final properties. Besides that, they show an extra-low carbon content, as its hardening mechanisms does not depend so much on this element. In the case of the HSLA-80 steel, copper precipitation represents a significant contribution to mechanical strength, whereas in the ULCB alloy this role is played by the bainitic microstructure and by the solid solution hardening effect promoted by substitutional alloy elements [8–12]. These approaches promote better weldability for both alloys. The simplification of the welding procedures can represent a 50% cost reduction during the fabrication of components and structures [5].

The aim of this work was to study the effect of thermomechanical processing over the mechanical properties of a copper precipitation-hardened steel (ASTM A710/HSLA-80) and an U.L.C.B. steel, as well to compare the characteristics of both alloys.

2. Experimental

The alloys studied in this work were produced in a vacuum melting furnace. Two 85 kg ingots were produced, one of HSLA-80 steel and the other of ULCB steel. The dimensions of each ingot were 100 mm × 130 mm × 850 mm. Their chemical analysis can be seen in Table 1.

The as-cast ingots were hot rolled in order to break and homogenize the as-cast structure. This step produced rectangular bars, with 50 mm × 42 mm cross-section. The blocks for the controlled rolling tests were machined from these bars. The dimensions of such blocks were 42 mm × 50 mm × 100 mm.

Two series of hot rolling tests were performed using a laboratory hot rolling mill. The first series was conceived to verify the effect of total strain applied during controlled hot rolling over the mechanical properties of both alloys. The several planned controlled rolling pass schedules and other related parameters can be seen in Table 2. During these tests the finishing temperature was kept constant for all blocks; its aimed value was 750 °C.

Another series of tests was included in order to study the effect of finishing temperature over the final mechanical properties of both alloys studied in this work. In this case the total strain applied during controlled rolling was constant, being chosen the maximum value feasible, that is, 50% during the roughing phase and 67% during the finishing phase, which resulted in a total hot rolling strain of 83%. Two finishing temperatures were applied in this series, that is, 700 and 800 °C. An additional finishing temperature, 750 °C, was already included in the first series of controlled rolling tests.

Two reheating temperatures were used in both test series, that is, 1100 and 1200 °C. The heating time of the blocks at the aimed austenitizing temperature was equal to 15 min. All rolling tests were followed by still air cooling.

It was considered vital that both alloys were submitted exactly to the same thermomechanical parameters. For this reason a block of HSLA-80 steel and another one of ULCB steel were always simultaneously hot rolled. To accomplish this need, previously to reheating and hot rolling, both blocks were held together using a special welded steel frame shown in Fig. 1; the dimension of such sets was 42 mm × 160 mm × 300 mm. This entire set was reheated and hot rolled according to the schedules planned. A chromel–alumel thermocouple inside a 3 mm diameter stainless steel sheath with mineral isolation was embedded in this frame, very near to the blocks, in order to record the temperature evolution during reheating, hot rolling and subsequent air cooling.

After hot rolling the frame was dismantled and the HSLA-80 and ULCB steel samples were separated and identified. Tensile and Charpy impact test samples were machined from these rolled samples. The tensile test samples were extracted in the longitudinal direction, whereas the Charpy test samples were machined in the transverse direction.

Table 1
Chemical analysis of the steels used in this study (wt.%)

Aço	C	Mn	Si	P	S	Al_{sol}	Ni	Cr	Cu	Mo	Nb	Ti	B	N
HSLA-80	0.044	0.65	0.32	0.005	0.011	0.013	0.87	0.77	1.12	0.23	0.077	–	–	0.0030
ULCB	0.033	1.93	0.29	0.007	0.011	0.006	0.39	–	–	0.35	0.062	0.029	0.0016	0.0030

Table 2
Laboratory controlled rolling schedules used for both steels studied in this work

Re-heating temperature (°C)		A		B		C		D	
		1200	1200	1200	1200	1100	1100	1100	1100
Roughing phase	True strain	0.36	0.36	0.69	0.69	0.36	0.36	0.69	0.69
	Reduction ratio (%)	30	30	50	50	30	30	50	50
Finishing phase	True strain	0.51	1.10	0.51	1.10	0.51	1.10	0.51	1.10
	Reduction ratio (%)	40	67	40	67	40	67	40	67
Total	True strain	0.86	1.46	1.20	1.79	0.86	1.46	1.20	1.79
	Reduction ratio (%)	58	77	70	83	58	77	70	83
Final thickness (mm)		17.6	9.8	12.6	7.0	17.6	9.8	12.6	7.0

Initial sample thickness: 42.0 mm.

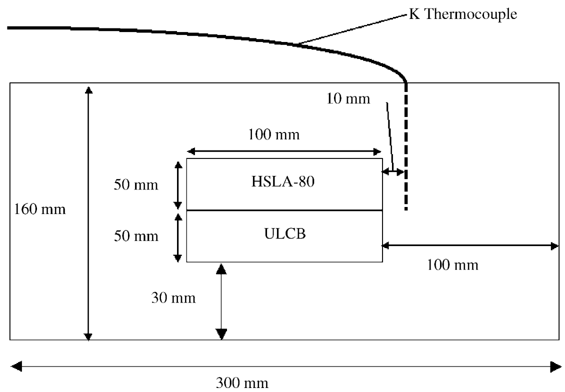

Fig. 1. Hot rolling set composed of the HSLA-80 and ULCB steel blocks for hot rolling embedded in a welded steel frame. This device allowed the simultaneous hot rolling of a sample of each steel, assuring that they were subjected exactly to the same parameters of the thermomechanical treatments.

All mechanical test samples were of the sub-size type, according to the ASTM A370 standard specifications. The machined tensile and Charpy impact samples of HSLA-80 were aged at 600 °C for 1 h. Finally, tensile and Charpy impact tests were performed using these samples. The samples for the Charpy impact tests were cooled down to −20 °C immediately before the test.

3. Results and discussion

As expected, yield strength increased as total strain applied during hot rolling raised, as shown in Fig. 2. The aged HSLA-80 steel samples showed yield strength clearly greater than the corresponding ones of ULCB steel, as well a slightly higher sensitivity towards total strain. The use of a higher slab reheating temperature promoted a slight increase in yield strength, but this effect tended to disappear when greater values of total strain were applied during hot rolling of the steel samples.

This figure also shows that all samples reached yield values at least equal to 551 MPa, a value equivalent to the minimum yield strength specified by the X-80 API Standard, except the ULCB samples reheated to 1100 °C and submitted to the lowest values of hot rolling strain, that is, 58 and 70%. Even so such samples showed values very near to this lower limit. The samples of aged HSLA-80 steel that were submitted to the highest strain levels during hot rolling showed values equal or greater than 699 MPa, a yield stress level typical of API X-100 plates.

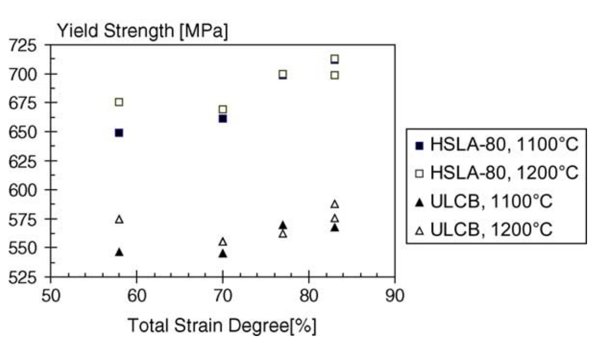

Fig. 2. Evolution of the yield strength of the HSLA-80 (aged) and ULCB (as rolled) steels according to the total strain applied during the rolling tests.

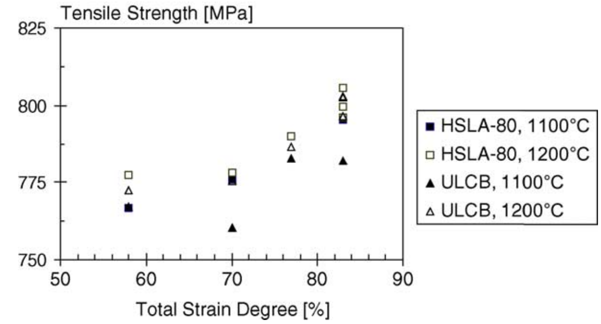

Fig. 3. Evolution of the tensile strength of the HSLA-80 (aged) and ULCB (as rolled) steels according to the total strain applied during the rolling tests.

Fig. 3 shows that also the tensile strength tended to increase according to the total strain value applied during hot rolling. The rise in reheating temperature also promoted a slight increase in the tensile strength values of both alloys. The difference observed between the values of tensile strength of corresponding samples of aged HSLA-80 and ULCB steel were lower than those observed for the yield strength. And the tensile strength values of samples of ULCB steel reheated at 1200 °C were slightly greater than the corresponding samples of aged HSLA-80 steel re-heated at 1100 °C.

As one can expect from the values got in this work about the values of yield and tensile strength, the yield ratio was greater for the samples of aged HSLA-80 steel than those of ULCB steel, as shown in Fig. 4. The higher values reached by the aged HSLA-80 samples, that varied between 85 and 90%, certainly impair the formability of this material, as it has a higher probability to show springback during the forming of pipes from plates. Besides that, this relatively small difference between yield strength and tensile strength narrows the safety margin of the equipments built with this alloy in case of an eventual mechanical overburden. The samples of this alloy

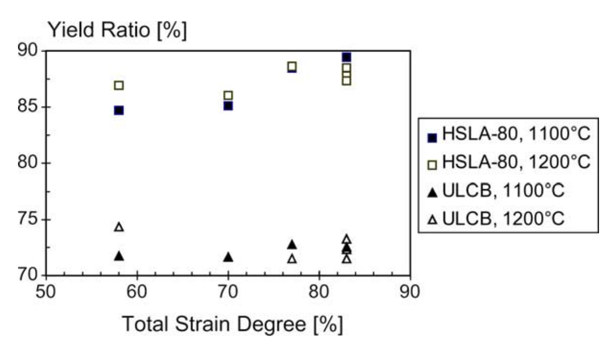

Fig. 4. Evolution of the yield ratio of the HSLA-80 (aged) and ULCB (as rolled) steels according to the total strain applied during the rolling tests.

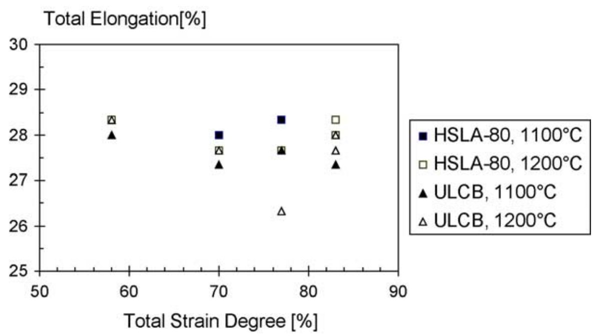

Fig. 5. Evolution of the total elongation of the HSLA-80 (aged) and ULCB (as rolled) steels according to the total strain applied during the rolling tests.

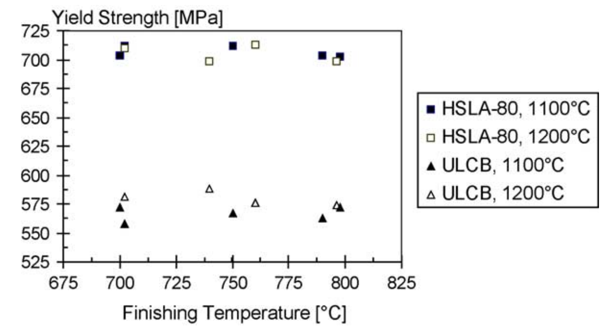

Fig. 7. Evolution of the yield strength of the HSLA-80 (aged) and ULCB (as rolled) steels according to the finishing temperature applied during the rolling tests.

also showed a tendency to have their values of yield ratio increased as the total strain applied during hot rolling became higher. This fact did not happen with the samples of ULCB steels, which values of yield strength were relatively constant, independently of the value of total strain applied during hot rolling.

The total elongation apparently was not affected in a significant way for both steels, neither by increasing the total strain applied during hot rolling, nor by increasing reheating temperature, as can be seen in Fig. 5. The aged HSLA-80 steel showed a very slight better ductility than ULCB steel, particularly for maximum levels of total strain applied during hot rolling.

The effect of total strain applied during hot rolling over steel toughness was very significant for both steels, but particularly for the aged HSLA-80 alloy. This is the conclusion that can be drawn from the data showed at Fig. 6. The ULCB steel was tougher than the aged HSLA-80–no wonder about this, as the ULCB alloy showed a slightly lower level of strength and had a smaller contribution from precipitation hardening. The samples reheated at lower temperature, 1100 °C, tended to be slightly tougher; in the case of ULCB steel this toughness increase was lower and became null for higher strain levels applied during hot rolling.

The slight increase of mechanical strength and toughness decrease observed when reheating temperature was risen from 1100 to 1200 °C could be due to an increase in the amount of soluble Nb promoted by the higher austenitizing temperature. Certainly the amount of soluble Nb after hot rolling also increased in such conditions, promoting an enhanced hardening effect by the precipitation of niobium carbonitride in the acicular ferrite/bainite during the ageing of HSLA-80 steel and during air cooling after hot rolling of the ULCB alloy. As it is widely known, such kind of hardening impairs toughness.

The increase of strength and toughness that was observed when total strain degree during hot rolling was risen certainly can be explained by the grain refining effect that these more severe forming conditions caused.

The influence of the finishing temperature over yield strength, depicted in Fig. 7, was virtually negligible. These values indicates that the aged HSLA-80 and the ULCB steel reached yield strength levels compatible with those specified by the API X-100 and X-80 standards respectively, no matter which finishing temperature was used.

Also in the case of tensile strength it was not possible to verify a consistent influence of the finishing temperature, as data present in Fig. 8 indicates. The fluctuations observed are small and random, particularly in the case of the ULCB steel. The effect of reheating temperature and steel composition were also not apparent.

Consequently, no significant finishing temperature effects were detected over yield ratio, as shown in Fig. 9. The same

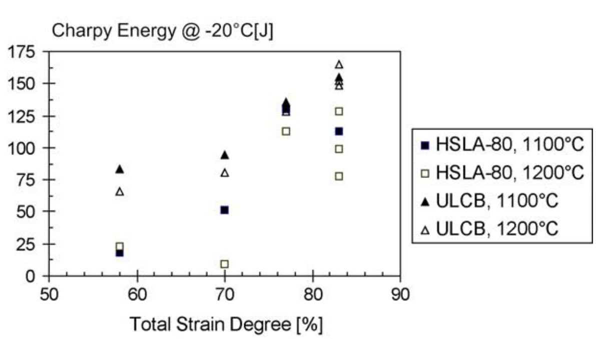

Fig. 6. Evolution of the Charpy energy absorbed at −20 °C of the HSLA-80 (aged) and ULCB (as rolled) steels according to the total strain applied during the rolling tests.

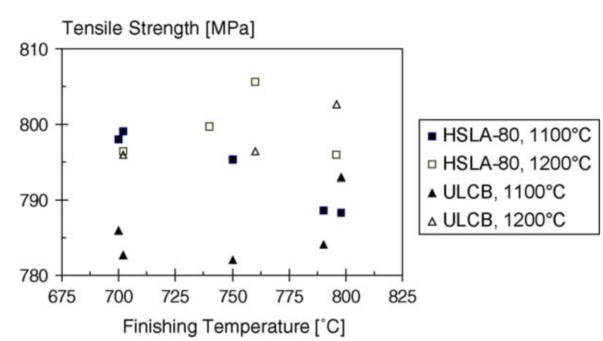

Fig. 8. Evolution of the tensile strength of the HSLA-80 (aged) and ULCB (as rolled) steels according to the finishing temperature applied during the rolling tests.

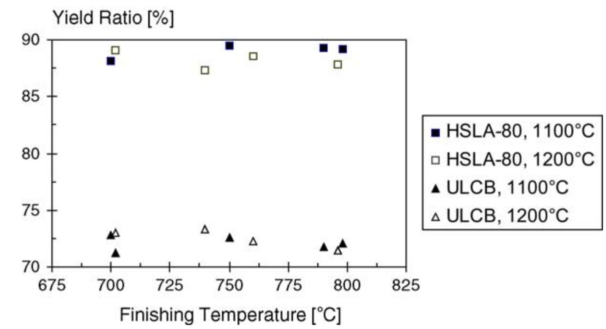

Fig. 9. Evolution of the yield ratio of the HSLA-80 (aged) and ULCB (as rolled) steels according to the finishing temperature applied during the rolling tests.

fact was observed about the influence of reheating temperature. However, as already shown in Fig. 4, the kind of steel decisively affected the values of yield ratio got: once again aged HSLA-80 steel showed far higher values than ULCB steel.

The result shown in Fig. 10 apparently indicates that the increase of the finishing temperature promoted a slight reduction in the ductility of both steels, irrespectively of their reheating temperature. Here again the aged HSLA-80 steel showed a slightly better ductility than the ULCB alloy.

But, once again, it was toughness that was significantly changed due to a modification in the controlled rolling process. The results exposed in Fig. 11 show that the increase in the finishing temperature lead to a great decrease in toughness, particularly in the case of the aged HSLA-80 steel. Once more the ULCB steel showed a better performance considering this aspect.

Apparently the grain refining effect that certainly was promoted by the finishing temperature decrease from 800 to 700 °C was not significant to lead to a change in mechanical strength. However, it was enough to enhance toughness of both alloys, but mainly of the samples of aged HSLA-80 steel that were reheated at 1200 °C. As the HSLA-80 samples were all aged their toughness performance, which is decreased by the precipitation hardening promoted by Cu and Nb, is specially impaired by the use of higher austenitizing temperatures, lower total strain applied during hot rolling and higher finishing temperatures.

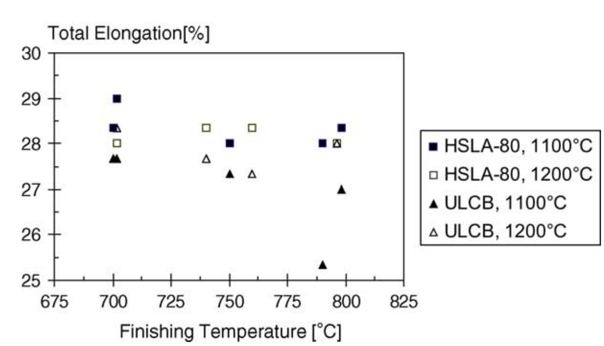

Fig. 10. Evolution of the total elongation of the HSLA-80 (aged) and ULCB (as rolled) steels according to the finishing temperature applied during the rolling tests.

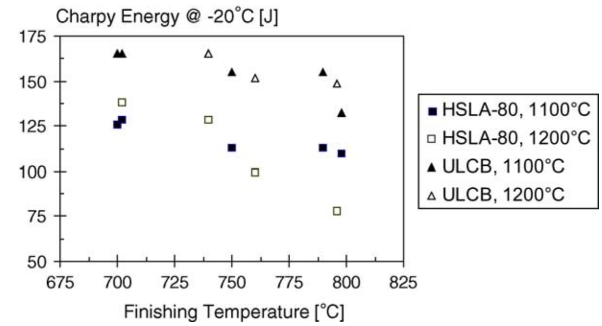

Fig. 11. Evolution of the Charpy energy absorbed at −20 °C of the HSLA-80 (aged) and ULCB (as rolled) steels according to the finishing temperature applied during the rolling tests.

4. Conclusions

The HSLA-80 and ULCB steels are extra-low-carbon alloys originally developed to replace quenched and tempered steels with tensile strength in the range from 600 to 800 MPa. A famous example of such kind of steel to be replaced is the HY-80 alloy. This work aimed to point the influence of some hot rolling parameters on the mechanical properties of such new extra-low-carbon steels. The effect of reheating temperature was not very important: generally higher values of such parameter lead to a discreet increase in strength and decrease in toughness levels. Toughness of both alloys was strongly improved as total strain degree during hot rolling increased. This effect was particularly important for the aged HSLA-80 alloy. The increase in the total strain degree also lead to slight higher strength levels in both steels. No effects were detected in the ductility of both materials. The decrease in the finishing temperature also increased markedly toughness of both alloys, but with an effect not as intense as verified for the total strain degree. This decrease in finishing strength barely affected mechanical strength and promoted a very slight ductility increase.

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