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Effect of controlled-rolling parameters on the ageing response of HSLA-80 steel

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ABSTRACT

The addition of copper to microalloyed steels in order to promote precipitation hardening is one of the approaches adopted to develop new materials with high mechanical strength but minimized carbon content to assure good weldability. Besides that, the thermomechanical processing of such alloys can eliminate the subsequent quench and tempering heat treatments required by conventional steels. The effects of controlled-rolling parameters over the ageing response of an HSLA-80 microalloyed steel with 1.10% copper were studied in this work. The relatively weak influence over the ageing response verified when the reheating temperature was elevated from 1100 °C to 1200 °C indicated that copper precipitation is the main mechanism behind the hardening promoted by the ageing treatment; niobium had a secondary role. The strain degree applied during the roughing phase increased the ageing response of the alloy, but an increase in the strain degree applied during the finishing phase had no effect over this aspect. Also, a finishing temperature variation had no significant effect on the ageing response of the HSLA-80 steel.

1. Introduction

The minimization of carbon content in structural steels has became a true obsession for steel metallurgists during the last decades, as this alloy element significantly degrades the weldability of such materials. However, carbon has a vital participation in the hardening mechanisms applied in conventional steel alloy design. This situation motivated the development of several alternative alloys to produce plates with equivalent mechanical strength but minimized carbon content. In the specific case of steel plates one can mention, for example, the hardening through copper precipitation in ferrite of HSLA-80 steel (Wilson et al., 1988).

Copper precipitation in ferrite can contribute significantly to steel strength. This alloy element does not form intermetallic compounds with iron; the atomic diameter of both is quite similar. The maximum solubility of copper in austenite is 2.4% at 840 °C (Hornbogen and Glenn, 1960). The age hardening of copper steels, generally performed under temperatures from 500 °C to 600 °C, promotes the precipitation of copper-rich ε particles, with diameter from 2 nm to 45 nm. This phase preferentially nucleates inside dislocations inside ferrite grains, as well as their boundaries and sub-boundaries (Wilson et al., 1988). Electronic diffraction patterns showed that ε precipitation is mostly constituted of copper, with a lattice parameter slightly higher than that of pure metal (Hornbogen and Glenn, 1960) and can contain up to 4% iron (Wriedt and Darken, 1960). In commercial microalloyed steels there is in practice a simultaneous copper and niobium precipitation, as the temperature range normally used favors this occurrence (Krishnadev and

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Galibois, 1995). It has been shown that precipitation hardening decreases toughness, so this hardening mechanism must be judiciously applied (Wilson et al., 1988).

Although copper precipitation hardened microalloyed steels are already being used since 30 years ago, relatively few studies were developed about the effect of controlled-rolling parameters over the age hardening response of such material. For example, it is known that the use of accelerated cooling immediately after hot rolling enhances this response, as there is less time available for an undesired copper precipitation in austenite during plate cooling (Abe et al., 1987). It was also determined that, if hot rolling finishing temperature is lower than the alloy Ar_3 temperature, age hardening response of the as-rolled material is much lower than that observed when it is reaustenitized after hot rolling. In some cases this response can be virtually null. The reason for this decrease in hardening effect could be a possible ε dynamic precipitation in the metastable austenite under temperatures below Ar_3 point (Banerjee et al., 2000).

This work will show the results got about the effects of some controlled-rolling process parameters over the age hardening response of a microalloy HSLA-80 structural steel.

2. Experimental procedure

The HSLA-80 steel studied in this work was melted in a laboratory vacuum induction furnace and poured in a cast iron mould. The ingot had weight of about 85 kg, 100 mm × 130 mm rectangular section and 850 mm of length. Its chemical analysis was 0.044% C, 0.65% Mn, 0.32% Si, 0.005% P, 0.011% S, 0.013 Al_{sol}, 0.87% Ni, 0.77% Cr, 1.12% Cu, 0.23% Mo, 0.077% Nb and 0.0030% N. The ingot was rough rolled to break and homogenize the as-cast structure. All hot rolling tests described in this work were carried out using a 2-Hi Ono-Roll laboratory rolling mill with table width of 300 mm. The specimens for the hot rolling tests were machined from these as-rough rolled rectangular bars, with 50 mm × 42 mm section. The dimensions of the hot rolling specimens were 42 mm × 50 mm × 100 mm.

Two series of rolling trials were carried out to study the effect of controlled-rolling parameters over age hardening response of HSLA-80 steel. The first one aimed to verify the effect of total strain degree applied to the specimens, as well its distribution between the roughing and finishing stages of controlled rolling, according to the pass schedules A–D shown in Table 1. Two reheating temperatures were used for each pass schedule: 1100 °C or 1200 °C; aimed finishing temperature was fixed at 750 °C.

Table 1 – Pass schedules applied in the controlled-rolling trials performed in this work

Parameters	A	B	C	D
Roughing strain				
Real	0.36	0.36	0.69	0.69
Nominal (%)	30	30	50	50
Finishing strain				
Real	0.51	1.10	0.51	1.10
Nominal (%)	40	67	40	67
Total strain				
Real	0.86	1.46	1.20	1.79
Nominal (%)	58	77	70	83
Final thickness (mm)	17.6	9.8	12.6	7.0

The other test series was performed in order to study the effect of finishing temperature. In this case samples were exclusively reheated at 1200 °C and rolled according only to the D pass schedule shown in Table 1. Aimed finishing temperatures were 700 °C, 750 °C or 800 °C.

The hardness of the as-rolled specimens was measured along their transversal sections with an Akashi durometer, AVK model, using Vickers scale with 5 kg load. All surfaces were ground and polished previously to the hardness measurements. Ten hardness values were measured along the diagonal of the major face. This was done aiming to minimize the influence of eventual segregations and/or orientations present in the samples.

Thereafter the as-rolled samples were aged at 600 °C during 1 h. These conditions were previously determined aiming at optimization regarding mechanical strength and toughness for the final plate (Gorni and Mei, 2004). Hardness measurements were also performed in the aged specimens, according to the same conditions described before. The response to ageing corresponds to the hardness difference between as-rolled and aged samples.

3. Results and discussion

The reheating temperature increase from 1100 °C to 1200 °C promoted a slight decrease in the hardness of the as-rolled and aged samples, as shown in Fig. 1a. This fact was consistent with the weak effect of reheating temperature over yield and tensile strength verified for these same aged HSLA-80 samples (Gorni and Mei, 2005). However, according to Fig. 1b, precipitation hardness was clearly greater for samples reheated at 1200 °C, probably indicating a slightly greater effect from an

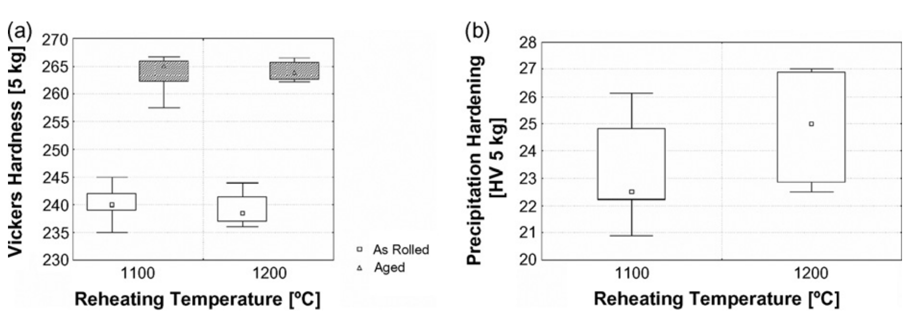

Fig. 1 – Reheating temperature effect over (a) as-rolled and aged hardness and (b) precipitation hardening.

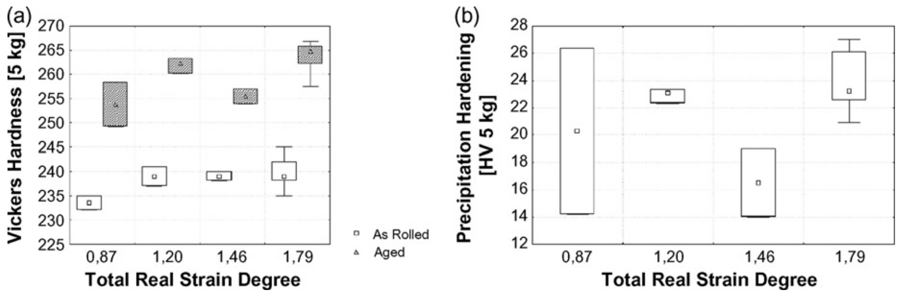

Fig. 2 – Total hot rolling strain degree effect over (a) as-rolled and aged hardness and (b) precipitation hardening.

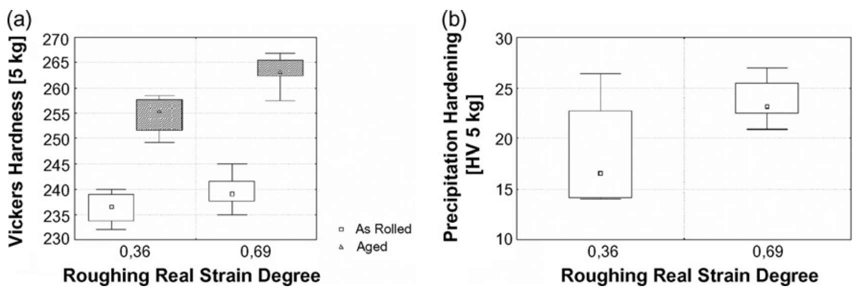

Fig. 3 – Roughing strain degree effect over (a) as-rolled and aged hardness and (b) precipitation hardening.

increased amount of solute niobium, but much lower than that observed for copper.

An increase in reheating temperature can promote contradictory effects over the age hardening response of the HSLA-80 steel. Higher austenitizing temperatures increase the amount of solute niobium, that is, promote greater precipitation potential during ageing treatment. The forecast value of solute niobium for this HSLA-80 steel after a 1200 °C reheating is over twice the calculated value if it was done at 1100 °C: 0.032% versus 0.015%, respectively (Gorni, 1998). Lower reheating temperatures promote finer austenitic grain sizes, as shown in Table 2 (Gorni, 2001). Evidence in literature (Wilson et al., 1988; Gladman, 1997) reports that a finer grain size leads to a finer copper precipitation, increasing its hardening effect. So, the final result from a variation in the reheating temperature over age hardening response will be function of the net result between these contradictory trends.

The effects of total strain degree over hardness values of the as-rolled and aged samples were very weak, as Fig. 2a shows. A comparison between samples submitted to extreme levels of strain degree (that is, 0.87 and 1.79) shows a discrete higher hardness for the samples submitted to the greatest strain degree. However, this effect is ambiguous for the other cases. The precipitation hardening response showed a similar trend, as seen in Fig. 2b.

Table 2 – Effect of reheating temperature and strain degree over austenite mean grain size after reheating and roughing stage during controlled rolling of the same HSLA-80 steel studied in this work (Gorni, 2001)

T_{reheat} (°C)	Grain size after reheating (μm)	Grain size after roughing (μm)	
		$\varepsilon_{esb} = 0.36$	$\varepsilon_{esb} = 0.69$
1100	82 ± 4	64 ± 3	24 ± 1
1200	102 ± 4	52 ± 2	32 ± 1

The effect of strain degree applied during the roughing phase has interesting aspects, as Fig. 3a shows. This effect was not very intense in the case of the as-rolled samples, but much more significant in the aged ones. The precipitation hardening results, Fig. 3b, confirmed this tendency. This explains the apparently ambiguous results shown in Fig. 2b, where samples submitted to a total strain degree of 1.20 showed a greater precipitation hardening than those submitted to a higher value of 1.46. As indicated in Table 1, in the first case strain degree applied in the roughing phase was equal to 0.69, while in the second it assumed a value of 0.36. The enhanced effect in the ageing response promoted by a increase in strain degree during the roughing stage could be explained due to the greater grain refining effect verified under these conditions, as shown in Table 2 (Gorni, 2001).

Strain degree applied during the finishing stage had a very modest effect in the hardness of both as-rolled and aged samples, as shown in Fig. 4a, and practically no effect in the ageing response, Fig. 4b. In this case it was observed only a wider dispersion in the precipitation hardening results got for the greatest strain degree applied during finishing stage.

According to the literature (Gladman, 1997), an increase in the strain applied during the finishing stage of controlled rolling would lead to an even greater age hardening response, as there is no more austenite recrystallization under these relatively lower rolling temperatures. The resulting strain hardening would promote a greater grain refining effect than that verified when deformation is applied in the high temperature range, when austenite recrystallizes quickly. But this tendency was not observed here. According to the literature (Banerjee et al., 2000), this loss in the age hardening response can be associated to copper precipitation in the strain hard-

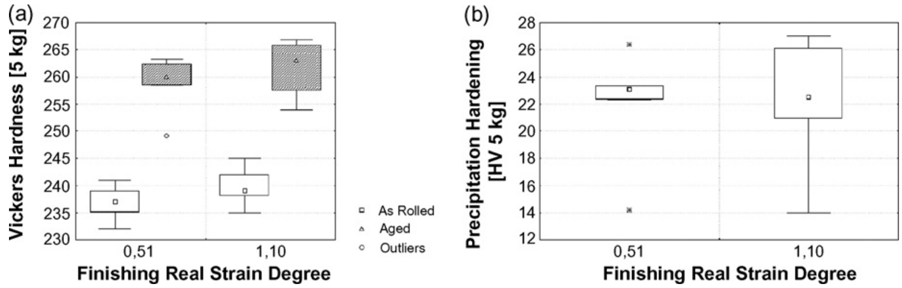

Fig. 4 – Finishing strain degree effect over (a) as-rolled and aged hardness and (b) precipitation hardening.

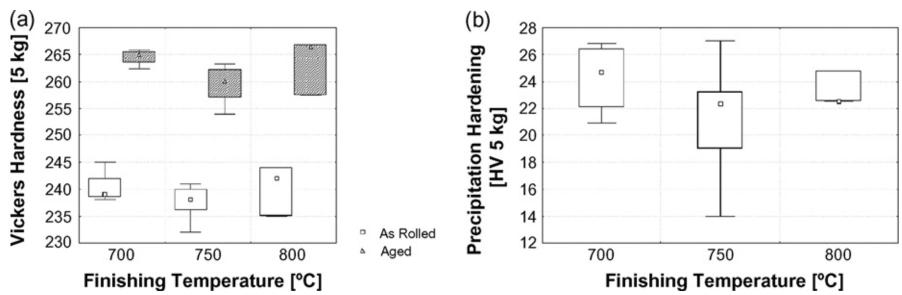

Fig. 5 – Finishing temperature effect over (a) as-rolled and aged hardness and (b) precipitation hardening.

ened metastable austenite, at temperatures lower than the Ar_3 point, which does not promote hardening. The increase in the strain hardening degree of austenite, associated to greater strains applied during the finishing stage, would enhance this kind of precipitation, counterbalancing the possible effects that grain refining could have over ageing response.

Lower finishing temperatures did not produce significant effects over hardness values got in the as-rolled nor in the aged specimens, as Fig. 5a shows. According to Fig. 5b, apparently the ageing response would be slightly greater in the case of the lowest finishing temperature – that is, 700 °C – but this conclusion is not statistically supported due to the wide data dispersion. So, as it was previously seen (Gorni and Mei, 2005), a finishing temperature variation in the 700–800 °C range did not influence significantly the mechanical properties of the HSLA-80 steel.

Finally, it must be considered that the ageing conditions applied here – 1 h at 600 °C – aimed a balance between mechanical strength and toughness, and not a maximum ageing response (Gorni and Mei, 2004; Gorni and Mei, 2005). The slight over-ageing applied to the samples of this work could have contributed to mask the relationships between process parameters and ageing response.

4. Conclusion

The results of this work show that the effect of process parameters of controlled rolling over the ageing response of an age hardenable HSLA-80 microalloyed steel was not very significant within the ranges applied. Apparently most of the hardening effect is due to copper precipitation, with niobium having a discrete role, as demonstrated the weak effect associated with the increase in the reheating temperature from 1100 °C to 1200 °C. The increase in the strain degree applied during the roughing phase intensified the ageing response, but no significant effects were detected by greater values of finishing strain degree, as well by finishing temperature variation between 700 °C and 800 °C.

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