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Citation: AIP Conference Proceedings **1896**, 130007 (2017);
View online: https://doi.org/10.1063/1.5008156
View Table of Contents: http://aip.scitation.org/toc/apc/1896/1
Published by the American Institute of Physics

Hot Rolled High Al Containing Steels as a Replacement for the Control Rolled High Strength Low Alloy (HSLA) Steels

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Abstract. The extent to which Al and Nb can be used to improve the properties of hot rolled steels has been investigated with the aim of obtaining mechanical properties similar to those given by the more expensive, control rolled or normalised route, eg. API X52 line pipe. Three steels with 0.02%Al, 0.16%Al and 0.16%Al, 0.018%Nb have been examined and their strength and impact behaviour obtained. The 0.16%Al steel had a similar strength to the 0.02%Al containing steel~300MPa, but better impact behaviour (30-40°C lower 54J, ITT) with an impact transition temperature (ITT) of -90°C which from previous work will be due to a refinement of the grain boundary carbides. The present work shows that the addition of Nb to this high Al containing steel, although beneficial to strength, giving a lower yield strength (LYS) of 385 MPa, close to that given by some of the control rolled steels gives very poor impact behaviour with a 54J ITT of only -20°C. The improvement of strength is mainly a result of precipitation hardening by NbCN with some benefit from grain refinement while the deterioration of impact behaviour might be due to the presence of lower transformation products or coarser carbides. Further work is required to positively clarify the cause of this deterioration and to explore further options in achieving the aim of obtaining a hot rolled steel with strength in the range 350-400MPa and 54J ITT of -50°C.

Keywords: Hot rolled steel, Aluminium, Niobium, Strength, Impact Transition Temperature (ITT)

INTRODUCTION

Control rolled steels are characterised by their excellent mechanical properties and are employed in many demanding engineering applications. The control rolling process involves refinement of grain size, giving higher strength and an improvement of notch toughness. However, the cost factor and the unavailability of the control rolling facilities in many of the smaller steel plants make it important to explore alternative options. Hot rolling is cheaper than the control rolling process but the mechanical properties are poor due to the coarser grain structures giving inferior impact resistance and lower strengths. Properties are improved on normalising but this adds considerably to costs.

The mechanical behaviour of hot rolled steels are affected significantly by their alloying composition, thus understanding the role of alloying elements in steel and specifying their optimum quantity in the composition may result in competitive hot rolled steels which can replace the control rolled steels at the lower strength end of the control rolled strength spectrum, (350-400MPa). Currently, research work has focused on aluminium as an addition to play the major role in improving the impact behaviour of hot rolled HSLA (high strength low alloy) steels. Previous research work indicated that a high Al content (~0.2%Al, is the optimum value) improves the impact behaviour of hot rolled steels [1-3] due to the refinement of the grain boundary carbides [3].

However, the amount of Al in solution must be restricted because Al increases hardenability and encourages martensite formation causing the impact behaviour to deteriorate and since martensite causes pre-yielding this often results in a lower yield stress [3]. In order to reach higher strength levels in these hot rolled steels, to be more in accord with those of control rolled steels, Nb has been added to provide both precipitation hardening and grain refinement. A low C content of 0.06% was selected to help avoid lower transformation products such as martensite and bainite. Silicon levels have also been raised to 0.5% as previous work has shown that higher Si levels can increase both strength and improve the impact behaviour [4]. S and P were also low to help enhance the impact behaviour. The long term aim of the programme is to achieve a hot rolled steel having a yield point of 350-400MPa and a 54J, Charpy V notch impact transition temperature of -60 to -40°C.

Proceedings of the 20th International ESAFORM Conference on Material Forming
AIP Conf. Proc. 1896, 130007-1–130007-5; https://doi.org/10.1063/1.5008156
Published by AIP Publishing. 978-0-7354-1580-5/$30.00

EXPERIMENTAL

The steels were cast as 22 kg laboratory vacuum melts. The ingots were soaked at 1200°C and hot rolled to a thickness of 15mm, finish rolling at 950°C (FRT). The plates were air cooled from 950°C to room temperature; the cooling rate through the transformation being 33K/min. The base composition of the steels was ~0.06%C, 1.4%Mn, 0.5%Si, 0.005%S, 0.005%P and 0.008%N.

Duplicate tensile specimens were machined from the plates in the transverse direction and strained to failure using a cross head speed of 0.025cm min^{-1}. The samples had 55mm gauge length and were 10mm in diameter and were tested based on BS EN ISO 6892-1 standard. Charpy V notch impact samples were machined from the hot rolled plates in the rolling direction and were 55.60mm in length and 10.06mm in width and all specimens were notched in an identical way and were tested based on BS EN ISO 148-1 standard.

The volume fraction of the phases present was measured by point counting and the grain size by the linear intercept method. The outcomes of these measurements were used to relate the microstructure to the mechanical properties.

RESULTS

The composition of the steels (wt.per.cent) are given in **Table 1**. The microstructural, tensile and impact properties of the steels after hot rolling are presented in **Table 2**. The low Al containing steel (S1) had a slightly higher strength than the high Al containing steel (S2) of about 12 MPa but the addition of 0.018%Nb to the high Al steel has led to a considerable improvement in the steel's lower yield strength by ~92MPa (**Table 2**).

The Impact transition curves for the three hot rolled steels are shown in **Fig. 1** and the 54J, ITT values are given in **Table 2**. For the Nb free, Al containing steels (S1 and S2), the increase of Al content level from 0.02 to 0.16% has resulted in the impact transition temperature (ITT) decreasing by approximately 40°C. In contrast, the addition of Nb to this high Al containing steel (S3) has increased the 54J, ITT by ~70°C, (**Table 2**).

Table 1. Composition of steels examined low Al (S1), high Al (S2) and Nb high Al (S3), wt-%

Steel	C	Mn	Si	S	P	Nb	Al	N	Fe
S1	0.051	1.4	0.47	0.0043	0.005	-	0.02	0.009	Bal.
S2	0.060	1.4	0.46	0.0045	0.005	-	0.16	0.007	Bal.
S3	0.056	1.39	0.46	0.0046	0.005	0.018	0.16	0.006	Bal.

Table 2. Microstructural, tensile and impact properties for the low Al, high Al and Nb high Al containing steels

Steel	Al	Nb	Grain size, $mm^{-1/2}$	LYS (MPa)	UYS (MPa)	UTS (MPa)	Elongation (%)	ITT at 54J, (°C)
S1	0.02	-	6.60	305	352	451	38	-50
S2	0.16	-	6.25	293	336	448	34	-90
S3	0.16	0.018	7.90	385	397	539	27	-20

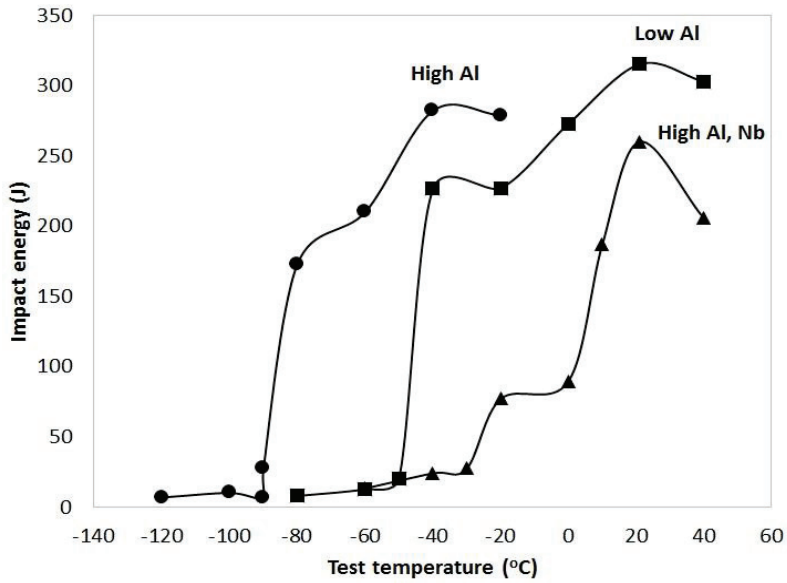

FIGURE 1. Impact transition curves of hot rolled steels for the low Al, high Al and Nb high Al containing steels

In examining the results it is normal to analyse them using empirical equations that have been developed for HSLA steels [5]. Any significant difference in the actual measured results with those predicted by these equations then warrants further investigation to establish the cause.

The experimental and predicted lower yield strength (LYS) values for the hot rolled steels are given in **Table 3** using the following equation developed specifically for hot rolled steels [5], LYS (MPa) for plain C-Mn steels having no precipitate hardeners:

$LYS = 105 + 43.1\%Mn + 83\%Si + 1540N_{free} + 15.4d^{-½}$ **Equation (1)**,
Where d is the average grain diameter ($d^{-1/2}mm^{-1/2}$) and the free N, N_{free} has been taken as the total N content even for steels, S2 and S3.

The equation for the 54J, ITT developed for HSLA steels having precipitation hardeners present is:

$54J, ITT\ °C = 192t^{1/2} - 10.1d^{-1/2} + 0.5\Delta Y - Constant$ **Equation (2)**,
Where t is the grain boundary carbide thickness in μm and ΔY (MPa) is the precipitation hardening contribution. $\Delta Y = LYS_{actual} - LYS_{Equation\ 1}$. The constant in **Equation 2** depends on the residuals present and sulphur content of the steel.

Table 3. Experimental and predicted LYS of the low Al, high Al and Nb high Al containing steels using equation (1)

Steel	Al	Nb	Experimental LYS (MPa)	Predicted LYS (MPa) Equation 1	Experimental Predicted LYS, (MPa)	Grain size Strengthening (MPa)	Normalised to S1, Grain size contribution (MPa)	ΔY Contribution (MPa)
S1	0.02	-	305	319	-14	102	0	0
S2	0.16	-	293	310	-17	96	-6	-11
S3	0.16	0.018	385	334	51	122	20	31

It can be seen from **Table 3** that the higher values of lower yield strength of the Nb containing steel (S3) is achieved mainly by precipitation hardening (ΔY = 31MPa) but the finer grain size also contributes to the strength, (20MPa), **Table 3**.

The microstructures of the hot rolled steels are shown in **Figs. 2a, b** and **c** for the 0.02%Al, 0.16%Al and 0.16%Al, 0.018%Nb, respectively. The phases present in all the steels are ferrite with a small amount of pearlite (~8%). The Nb free, Al containing steels (S1 and S2) show similar microstructures and grain size, (**Figs. 2a** and **2b**) whereas the Nb containing steel (S3) shows a bimodal grain size distribution with coarse grains similar in size to the hot rolled Nb free steels interspersed with a much finer ferrite grain size, **Fig. 2c**.

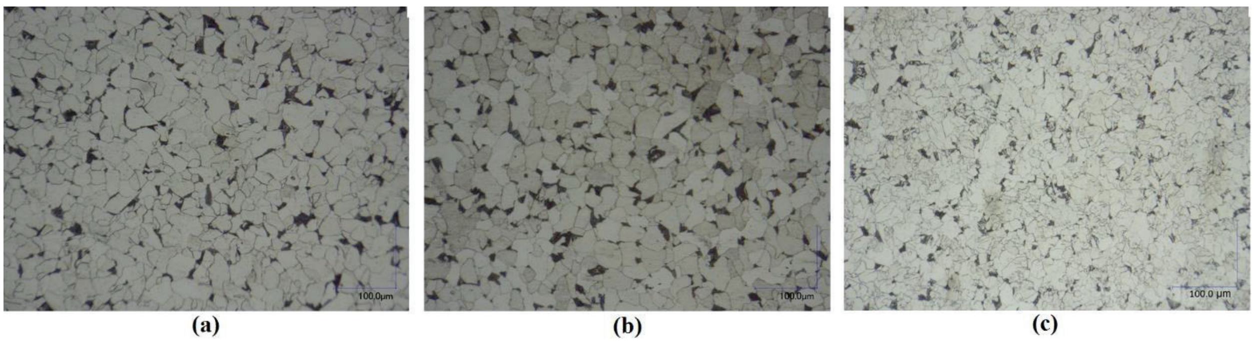

FIGURE 2. Ferrite/pearlite microstructures of (a) S1 hot rolled low Al containing steel (b) S2 hot rolled high Al containing steel (c) S3 hot rolled Nb high Al containing steel.

DISCUSSION

The high and low Al containing steels (S1 and S2) show similar strength levels despite the large difference in Al content. Indeed, the low Al containing steel (S1) gave a slightly higher strength, 12MPa higher, possibly due to both its slightly finer grain size (**Table 2**) and probably higher free N content as a result of the low Al content. By adding 0.16%Al, the steel had a lower yield strength of ~300MPa with a 54J, ITT of -90°C.

Generally, even without any further grain refinement from the Nb addition, increasing the strength by precipitation hardening alone to 400MPa should have resulted in an ITT of at least -40°C, (An increase of ΔY by 100MPa results in an increase in the 54J ITT of +50°C**,** according to **Equation 2**) not the obtained value of -20°C. Considering that the NbCN did do some grain refining (**Table 2** and **Fig. 2c**) the impact behaviour should have been even better. The poor impact behaviour, **Fig. 1,** therefore must due to some other reason than precipitation hardening.

The considerable improvement in the strength over the Nb free steels can be seen to be mainly due to precipitation hardening, (31MPa) but grain refinement also helps, (20MPa) (**Table 3**). The good impact behaviour of the high Al containing steel without Nb (S2), **Fig. 1** has from previous work [3] been shown to be mainly due to refinement of the grain boundary carbides by Al in solution. However, some of the improvement in impact performance for the higher Al containing steel, (S2)**,** over the low Al steel, (S1) may also be due to N removal.

It is known that both Al and Nb additions encourage the formation of martensite so particular care has to be taken when both alloying additions are present and high cooling rates are used during processing [3,6-8]. A recent study [6] has shown that Nb containing steels are more exposed to martensite formation leading to the creation of local brittle zones and influencing overall toughness and it is known that Nb lowers the transformation temperatures [7, 8].

Previous work [9] has also shown that Nb containing steels can give coarser carbides as well as an increase in their density, both of which cause a deterioration in impact performance. The thickness of the grain boundary carbide has been shown to be dependent on the temperature of the pearlite reaction [10] and this depends on both the grain size and the presence of Nb, as can be seen from the following empirical equation for the Ar3, [8],

Ar3 (undeformed) °C = 833.6 - 190.6%C - 67.4%Mn + 1522%S - 2296%N_{ti} -0.177CR - 1532%Nb + 7.91$D^{-1/2}$
Where CR = cooling rate K/min, D is the austenite grain size in range 100 to 1000μm **Equation (3)**.

This equation would only give a relatively small increase in the Ar3 of about 15°C, on refining the austenite grain size from 1000 to 100μm. Adding Nb can be seen from **Equation 2** to lower the Ar3 while refining the grain size raises the Ar3. However, Yuan et al [8] have shown a much bigger influence of austenite grain size on the Ar3 for this same grain size range in their equation would give an increase of 80°C. Hence although Nb lowers the transformation temperature, its grain refining ability may result in a higher transformation temperatures so that the carbides may indeed be coarser resulting in a lower than the expected improvement in impact behaviour. Although metallography has not shown any firm evidence for the presence of lower transformation products further work is required to confirm this and the carbide thickness of the steels needs to be determined.

SUMMARY

- The aim of the present work has been to develop a hot rolled steel having lower yield strength between 350 and 400MPa to replace control rolled steels of similar strength levels and more importantly to have similar impact behaviour.

- Adding 0.16%Al, resulted in a strength of ~300MPa similar to the plain C-Mn steel but the impact behaviour was much better at -90°C, the ITT being 40°C lower. Unfortunately, although the Nb containing steel gave the required strength, the ITT was much worse than expected, (-20°C). Generally, it is found that an increase in strength by 50-100MPa to attain the desired strength level of 350-400MPa, should have given rise to an increase in ITT of 25 to 50°C (**Equation 2**) i.e. resulting for the Nb containing steel in an ITT of -40 to -65°C not the -20°C given in this work.

- Previous work [7,8] has shown that Nb additions lead to coarser grain boundary carbides and this may be the cause of the poor impact behaviour. A more detailed microstructural examination is required to identify whether indeed the carbides are coarser in this Nb steel than present in the Nb free steels and further work needs to be carried out to achieve the aim of improving the impact behaviour of hot rolled steels.

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