Pipeline Technology, Volume II
R. Denys (Editor)

THE EFFECTS OF VANADIUM ON THE PARENT PLATE AND WELDMENT PROPERTIES OF ACCELERATED COOLED API 5LX100 STEELS

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SUMMARY

The effects of rolling schedule, finish rolling temperature, cooling rate through the transformation and vanadium level, with and without an addition of 0.25%Mo, on the properties of 15mm thick, accelerated cooled, plate of base composition 0.08%C/1.85%Mn/0.45%Si/0.05%Nb/Cu, Ni, Ti have been determined.

It has been demonstrated that plate of yield strength 100ksi, with >170J Charpy vee-notch energy absorption at -20°C, coupled with an 85% BDWTT transition temperature <-20°C, can be obtained using steel containing 0.08%V + 0.25%Mo, rolled by a schedule incorporating 20-21% deformation/pass in the temperature range 850-800°C, to finish rolling at 800°C, followed by cooling between 800 and 550°C at a rate exceeding 30°C/sec.

In expanded pipe, scope exists to reduce the vanadium level and cooling rate required for achievement of tensile properties.

An initial examination of the weldability, based on simulation of the longitudinal weld, indicates a satisfactory level of HAZ toughness, particularly in steel containing 0.08%V + 0.25%Mo. In addition, the preheating requirements for field welding appear to be similar to, but slightly higher than, those of existing API 5LX-80 steels.

1. INTRODUCTION

Since the launching of accelerated cooling after rolling of plate, in the early 1980's, there has been continuous development of the linepipe grades to which accelerated cooling is applied. Among other things this has led to the successful development of API 5LX65 for sour gas applications (1, 2) and API 5LX80 (3) for overland applications. Now that API 5LX80 has become an established grade, attention is being focused on even higher strength API 5LX100 linepipe.(4,5)

It is the intention, therefore, of the present paper to study the potential role of vanadium and of vanadium plus molybdenum in the manufacture of API 5LX100, accelerated cooled, linepipe. In addition the effects of some of the processing factors such as rolling schedule, finish rolling temperature and cooling rate on the mechanical properties will be examined and an indication of weldability obtained.

2. PROCEDURE

100Kgm, vacuum induction melts, of cross section 140 x 120mm, were manufactured. The chemical compositions and processing conditions chosen were, initially, based on previous work(6) which examined the effects of vanadium on the properties of API 5LX80 steels. As can be seen from Table 1, the main compositional variables were the vanadium level, which was varied between 0.0% and 0.15% and the molybdenum level, which was examined at 0.0% and 0.25%.

Table 1

Chemical Composition (wt %)

C	Si	Mn	Al	Cu	Ni	Mo	V	Ti	Nb	N
0.083	0.43	1.86	0.027	0.26	0.27	-	-	0.01	0.053	0.0050
0.08	0.44	1.89	0.027	0.26	0.27	-	0.08	0.011	0.054	0.0042
0.081	0.44	1.84	0.027	0.26	0.27	-	0.15	0.011	0.05	0.0042
0.081	0.44	1.84	0.028	0.26	0.27	0.24	-	0.011	0.05	0.0038
0.078	0.43	1.83	0.025	0.26	0.27	0.24	0.08	0.01	0.05	0.0038
0.082	0.44	1.84	0.026	0.26	0.27	0.24	0.15	0.01	0.05	0.0038

all steels contained 0.006%P, 0.002-0.003%S, <0.005%Ca

The ingots were reheated to 1100°C, held for 1-1.5 hours and pre-rolled into bars 120 x 100mm cross section. The bars were divided into six pieces which were, in turn, reheated to 1150°C, held for 1-2 hours and rolled to 15mm thick plate using the rolling schedules shown in Table 2.

In all of the rolling schedules the total reduction was 87.5% and the total amount of deformation, after the intermediate hold, was 67% in Schedules 1 and 2 and 69% in Schedule 3. Additionally, in Schedules 1 and 2 the reduction per pass and the start hold temperatures were the same but the finish hold and finish rolling temperatures were different. The finish rolling temperature in Schedule 1 was 800°C, while that in Schedule 2 was 700°C. In Schedule 3, the start and finish hold temperature and the finish rolling temperature were the same as in rolling Schedule 1. However, the total number of passes was eleven in Schedule 3, compared with thirteen in Schedule 1. This was achieved by reducing the number of passes in both the roughing and finishing stages of rolling by one. In addition, the deformation/pass in the final stages of rolling in Schedule 3 was 20-21%, compared with 13 - 21% in Schedule 1.

Table 2

Rolling Schedules

Schedule 1			Schedule 2			Schedule 3		
Time, secs	Temp, °C	Thick, mm	Time, secs	Temp, °C	Thick, mm	Time, secs	Temp, °C	Thick, mm
0	1150	120	0	1150	120	0	1150	120
20	1110	105	20	1110	105	20	1110	103
30		90	30		90	30		88
40		77	40		77	40		76
50		66	50		66	50		65
60		58	60		58	60		56
70		51	70		51	70	1020	48
80	1020	45	80	1020	45			
280	820	39	550	730	39	230	820	38
290		33	560		33	240		30
300		28	570		28	250		24
310		23	580		23	260		19
320		19	590		19	270	800	15
330	800	15	600	700	15			

Within 10 seconds of the end of rolling by Schedule 1, the plates were transferred to an accelerated cooling rig and cooled by water at cooling rates of 25°C/sec and 40°C/sec until a temperature of 500 - 550°C was reached. At this point, accelerated cooling was stopped and the plates were allowed to cool, naturally, in air. Similarly, after rolling, the plates rolled by Schedule 2 were cooled at 25°C/sec and 50°C/sec, while those rolled by Schedule 3 were cooled at 30°C/sec.

8mm round, transverse, tensile specimens and transverse, Charpy vee-notch impact specimens, centred on mid-thickness, were prepared and tested from each plate. Battelle drop weight testing was carried out on material rolled by Schedule 3. Metallographic examination was performed and the area fractions of the major phases present in each plate were ascertained.

Weld implant testing to DVS 1001 and simulated weld HAZ toughness testing was carried out on plates rolled by Schedule 3. In the HAZ simulation, the heating rate was 270°C/sec, the maximum temperature was 1350°C, the holding time at maximum temperature was 1 sec and Δt8/5 was 50 seconds, ie, approximately equal to a heat input of 4.0kJ/mm. The chemical compositions of the steels used in the weldability and Battelle DWTT assessments are shown in Table 3.

Table 3

Chemical Composition of Steels for Weldability and Batelle DWTT Assessment (wt%)

C	Si	Mn	Al	Cu	Ni	Mo	V	Ti	Nb	N
0.083	0.44	1.85	0.023	0.26	0.27	-	0.08	0.01	0.053	0.004
0.08	0.44	1.87	0.028	0.26	0.27	0.23	0.08	0.01	0.049	0.0037

all steels contained 0.006%P, 0.002%S, <0.005%Ca

3. RESULTS AND DISCUSSION

3.1. Tensile Properties

Figures 1 and 2 show the effect of vanadium on the yield strength and U.T.S of the plates finish rolled at 800°C. Figure 1 shows the results for the molybdenum-free steels, while Figure 2 shows the results for the steels which contained 0.25%Mo. As the level of free nitrogen is known to affect the degree of precipitation strengthening observed in vanadium-containing steels, the tensile properties have been plotted as a function of the vanadium-nitrogen product in these figures. It should be noted that all the steels used in this work contained titanium and the nitrogen level used when calculating this product assumed stoichiometric formation of TiN.

From Figures 1 and 2, it can be seen that 100 ksi yield strength was only just achieved in the molybdenum-free, 0.15%V, steel cooled at 40°C/sec. In the molybdenum-containing steels, 100 ksi yield strength was achieved at more intermediate levels of vanadium and cooling rate. This is illustrated more clearly in Figure 3 from where it can be seen that to achieve 100 ksi yield strength in parent plate of these steels it was necessary for the cooling rate to be greater than 30°C/sec, coupled with a vanadium level of at least 0.08%.

Figure 4 shows the effect of finish rolling temperature on the yield strength of steels containing 0.08%V. At lower cooling rates (25°C/sec), reducing the finish rolling temperature from 800°C to 700°C had little effect on the yield strength. However, at the higher cooling rates examined, reducing the finish rolling temperature resulted in a reduction in yield strength, such that 100 ksi yield strength was not achieved even in the steel containing 0.08%V+0.25%Mo, cooled at 50°C/sec.

The effect of cooling rate on the tensile elongation of steels finish rolled at 800°C is shown in Figure 5. Elongation fell with increasing cooling rate from a level of 18-24%, at 25°C/sec, to a level of 13-19%, at 40°C/sec. Furthermore, the

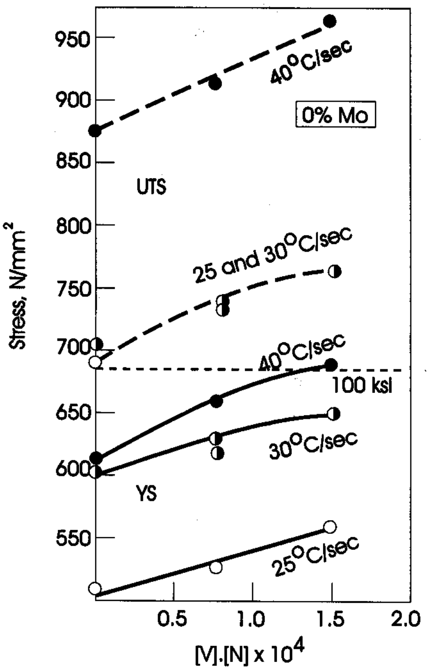


Fig. 1 The Effect of Vanadium-Nitrogen Product on the Tensile Properties of Accelerated Cooled 15mm Thick Plate of Composition 0.08%C/1.85%Mn/0.45%Si/0.05%Nb, Cu, Ni, Ti (FRT 800°C)

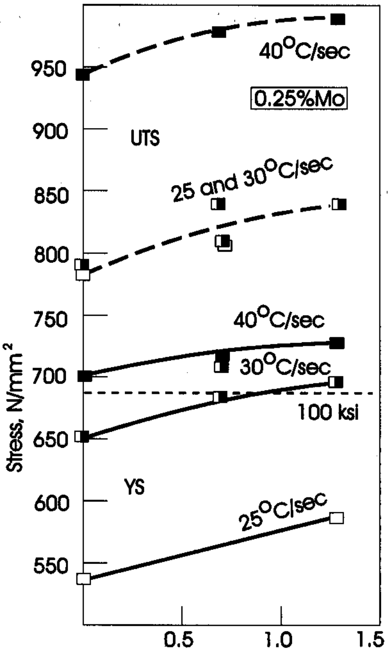


Fig. 2 The Effect of Vanadium-Nitrogen Product on the Tensile Properties of Accelerated Cooled 15mm Thick Plate of Composition 0.08%C/1.85%Mn/0.45%Si/0.05%Nb, Cu, Ni, Ti (FRT 800°C)

addition of vanadium and/or molybdenum tended to reduce the elongation by approximately 3.0%. However, at a cooling rate of 30°C/sec, the steel containing 0.08%V + 0.25%Mo and rolled by Schedule 3, had a tensile elongation of approximately 20%, which can be considered to be satisfactory.It should be noted that the levels of elongation observed in steels finish rolled at 700°C, were similar to those of the steels finish rolled at 800°C.

The levels of yield/U.T.S ratio observed for all steels were relatively good, the maxima being 0.86 and 0.87, depending on whether the steel was finish rolled at 800°C or 700°C, respectively.

The properties outlined above were for parent plate. However, in a pipe mill manufacturing linepipe by the U-O-E method, the opportunity exists to expand the pipe after cold forming and welding. While this process was not carried out on any of the steels under investigation, examination of the tensile curve at say the 2.0% proof stress gives an indication of the strength level likely to be observed in expanded pipe. Figure 6 indicates the effect of vanadium on this parameter for

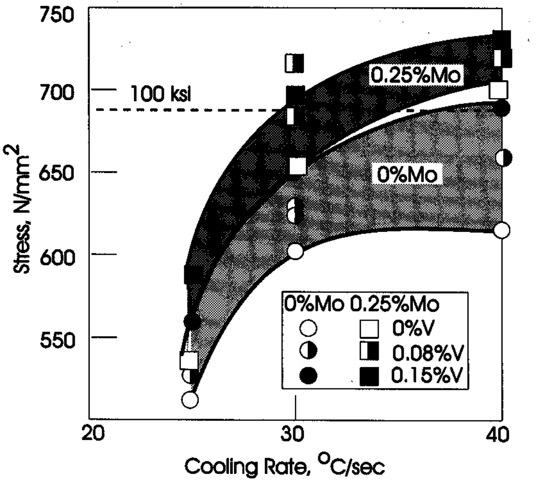


Fig. 3. Effect of Cooling Rate and Chemical Composition on the Yield Strength ($R_{t0.5}$) of 15mm Thick plate of Composition 0.08%C/1.85%Mn/0.45%Si/0.05%Nb, Cu, Ni, Ti Accelerated Cooled Steel (FRT 800°C)

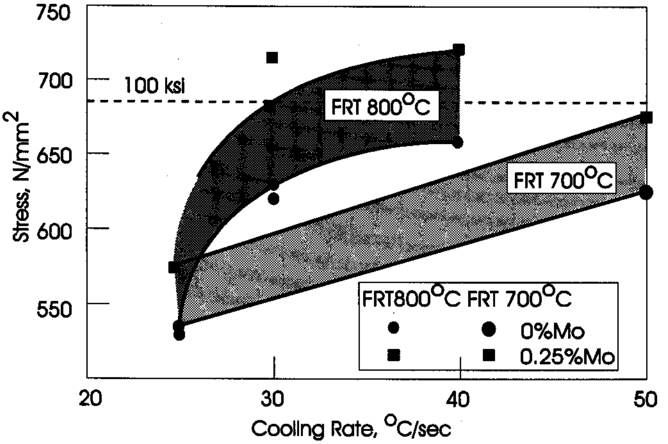


Fig. 4. Effect of Cooling Rate and Finish Rolling Temperature on the Yield Strength ($R_{t0.5}$) of 15mm Thick Plate of Composition 0.08%C/1.85%Mn/0.45%Si/0.05%Nb/0.08%V Cu, Ni, Ti Accelerated Cooled Steel.

steels cooled at 25°/sec and 30°C/sec, with and without the 0.25% molybdenum addition. These cooling rates were chosen for illustration in this figure because they probably represent the upper limit of cooling rate which can be controllably achieved on existing accelerated cooling systems, at 15mm thick. In the molybdenum-free steels finish rolled at 800°C (Figure 6a), a vanadium level greater than 0.08%, coupled with a cooling rate of 30°C/sec, or greater, were required to achieve a 2.0% PS of 100 ksi. In the corresponding steels containing 0.25%Mo, 100 ksi was achieved from zero vanadium upwards at both cooling rates. With the finish rolling temperature of 700°C, the picture was similar (Figure 6b). However, the margin by which the molybdenum-containing steels, cooled at 25°C, achieved 100 ksi was less than it was when the steels were finish rolled at 800°C.

If an allowance of say 40N/mm^2 is made for the Bauschinger effect, observed when flattened strap tensile tests are taken from pipe, then the present results indicate that a steel of the present base composition containing 0.04-0.06%V + 0.25%Mo, finish rolled at 800°C and cooled at between 25 and 30°C/sec, will be required in order to achieve the required yield strength in expanded pipe. While this finish rolling is higher than that indicated by Endo (5) the levels of vanadium, molybdenum and cooling rate are similar.

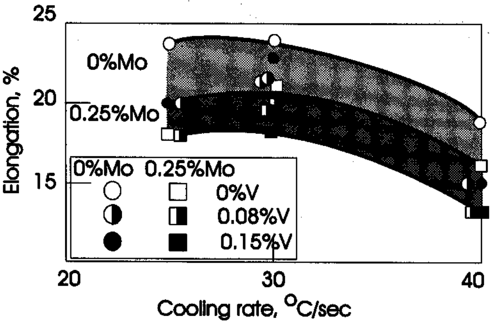


Fig. 5. The Effect of Cooling Rate and Chemical Composition on the Tensile Elongation of Accelerated Cooled, 15mm Thick Plate of Composition 0.08%C/1.85%Mn/0.45%Si/ 0.05%Nb, Cu, Ni, Ti (FRT 800°C)

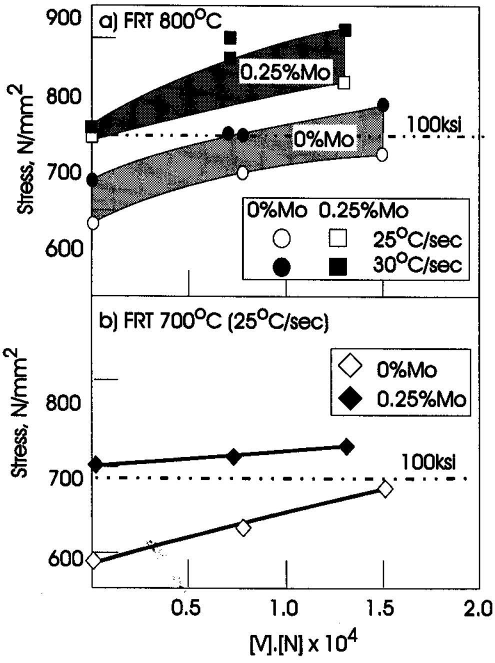


Fig. 6. The Effect of Vanadium, Molybdenum and Finish Rolling Temperature on the 2.0% Proof Stress in Accelerated Cooled 15mm Thick Plate of Composition 0.08%C/1.85%MN/ 0.45%Si/0.05%Nb, Cu, Ni. Ti

It is worth noting from Figures 1 and 2 that, if the accelerated cooling rate could be controllably increased to 40°C/ sec, significant improvement in strength and/or reduction in alloying is possible.

3.2. Impact Properties

Figure 7 shows the effect of vanadium - nitrogen product on the 100J ITT of steels finish rolled at 800°C and 700°C. In the main, increasing the level of the product, within the range examined, had relatively little effect on ITT. Where increases were observed it was only in the steels containing 0.15%V, or those cooled at the fastest cooling rates. Molybdenum also tended to increase the ITT and from Figure 7 it can be seen that the molybdenum-containing steels tend to lie towards the upper bounds of the respective scatter bands.

The most important feature illustrated in Figure 7 is the effect of rolling schedule on the impact properties. In Figure 7a) the steels rolled by Schedule 1 had ITT's in the range -35/-60°C, while those rolled by Schedule 3 had ITT's in the range -65/ -105°C. Thus, increasing the amount of deformation per pass in the final stages of rolling appears to have had a useful and beneficial effect on toughness. Furthermore, the results obtained by increasing the deformation per pass appear to be superior to those obtained by decreasing the finish rolling temperature to 700°C, shown in Figure 7b).

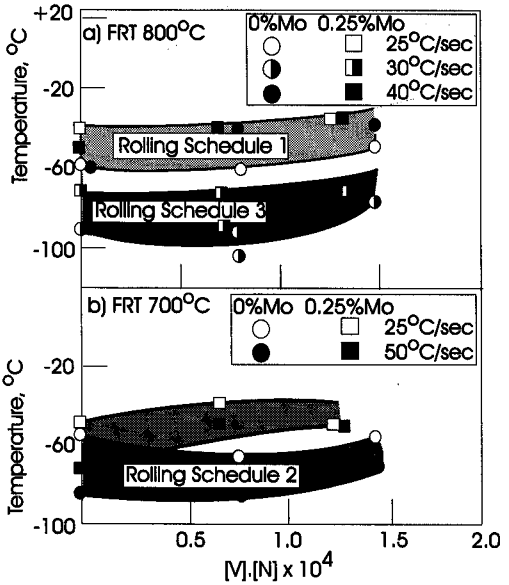


Fig. 7. The Effect of Chemical Composition, Rolling Schedule and Cooling Rate onthe Temperature for 100 Joules Energy Absorption in Accelerated Cooled 15mm Thick Plate of Composition 0.08%C/1.85%Mn/0.45%Si/0.05%Nb, Cu, Ni, Ti.

In linepipe, the ability to arrest a propagating shear fracture is of great importance and, following the approach of Endo (5), levels of Charpy vee-notch energy of 135-170J at -20°C are predicted as being required for 15mm thick, 42" diameter, linepipe, operating at a hoop stress of 490MPa. Figure 8 a) and b) shows the energy absorbed at -20°C by the steels used in the present investigation. Once again, the steels rolled by Schedule 3 exhibited the highest level of toughness, easily achieving the required levels of energy. Steels rolled by Schedule 2 (FRT 700°C), containing 0.08%V, or less, and cooled at 50°C/sec, were also satisfactory. However, as noted above, such a high level of cooling rate is probably not controllably feasible in current cooling units and the tensile properties were also lower than those of the steels finish rolled at 800°C.

3.3. Battelle Drop Weight Tear Tests

BDWT testing was carried out on samples of the 0.08%V and 0.08%V + 0.25%Mo steels which had been rolled by Schedule 3 and cooled at 30°C/sec. Results are given in Figure 9. From this it can be seen that the 0.08%V steel had an 85% shear transition temperature of -42°C, while the 0.08%V+0.25%Mo steel had a shear transition temperature of -27°C. These temperatures comfortably meet the most frequently required BDWTT requirement at -10°C. However, for Arctic pipelines, a value of 85% shear at -20°C has sometimes been suggested as being necessary. At this temperature both steels exhibited 97-98% shear and would, thus, have performed satisfactorily in this more demanding situation.

3.4. Microstructures

Accelerated cooled steels have microstructures which are typically bainitic, with varying amounts of ferrite and martensite making up the balance. Figure 10 summarises the main phases occuring in the steels under consideration. The main microstructural constituent was indeed bainite, (70-90%), followed by ferrite (10-20%), the remainder being martensite. Generally, there was little or no effect of vanadium on the phases present and steels containing molybdenum and/or those of faster cooling rates tended to have higher levels of bainite. There was also little or no effect of finish rolling temperature on the phases present. Previous work [(6)] on steels of similar base composition indicated transformation start temperatures of around 700°C, or less, hence the lack of effect of finish rolling temperature in the present results is, therefore, not surprising.

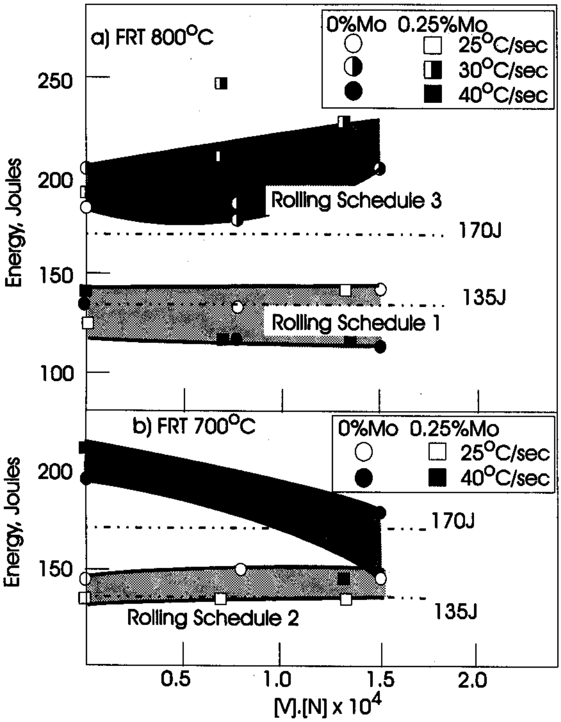


Fig. 8. The Effect of Chemical Composition, Rolling Schedule and Cooling Rate on the Energy Absorbed at -20°C in Accelerated Cooled 15mm Thick Plate of Composition 0.08%C/1.85%Mn/0.45%Si/0.05%Nb, Cu, Ni, Ti.

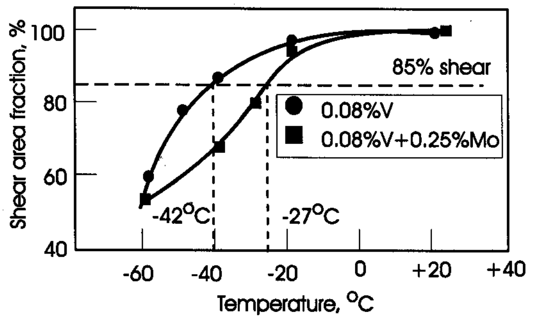


Fig. 9. BDWTT Results for 0.08%V and 0.08%V+0.25%Mo Steels Cooled at 30°C/sec

Transmission electron micrographs of the 0.08%V steel rolled by Schedule 3 and cooled at 30°C/sec are shown in Figure 11. Figure 11 (a) gives an indication of the relatively good distribution of carbon-rich phases contained within the ferritic matrix. Figure 11(b) indicates some fairly coarse precipitates. Microanalysis of a small number of these precipitates indicated that they fell into two distinct groups. The first of these groups was Ti-rich and had the average composition 56.6%Ti/40.4%Nb/3.0%V (At%), while the second was rich in Nb and had the average composition 83.8%Nb/14.0%Ti/2.2%V (At%). The sizes of the particles in the two groups appeared to be similar and to lie in the range 10-40nm. From this it is likely that they precipitated either during casting and subsequent cooling, in the case of the Ti-rich particles, or during rolling, in the case of the Nb-rich particles. It would also appear that the majority of the vanadium remained available for precipitation during subsequent cooling.

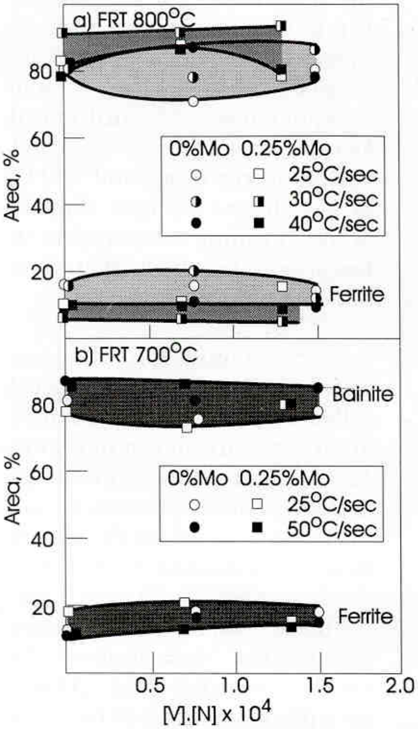
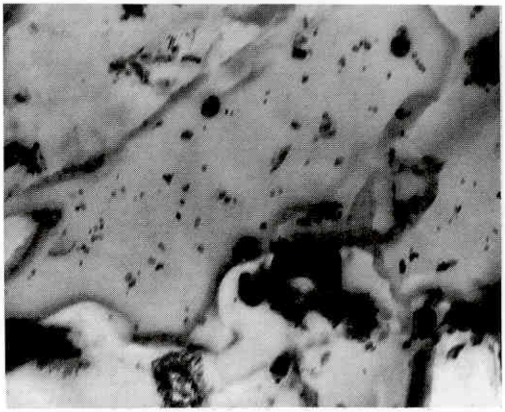


Fig. 10. The Effect of Vanadium-Nitrogen Product on the Microstructure of Accelerated Cooled 15mm Thick Plate of Composition 0.08%C/1.85%Mn/0.45%Si/ 0.05%Nb, Cu, Ni, Ti.

a) General Microstructure and Carbon Distribution x1500



b) Precipitate Distribution x20,000

Fig. 11. Transmission Electron Micrographs from 0.08%V+0.25%Mo Steel

Weld Heat Affected Zone Testing

HAZ Toughness

Charpy vee-notch impact transition temperatures from simulated welding carried out on the 0.08%V and 0.08%V + 0.25%Mo steels rolled by Schedule 3 are shown in Figure 12. Each point in this figure represents the average of between three and six specimens. It can be seen that at the lower temperatures examined the 0.08%V + 0.25%Mo steel exhibited a higher level of toughness than the 0.08%V steel. The former steel recorded 40J average at -20°C while the latter recorded 40J average at -5°C. These results indicate similar levels of toughness to those reported in simulations carried out on API 5LX-80 steels at similar cooling times(7). However, it should be noted that the transition temperatures are higher than reported for

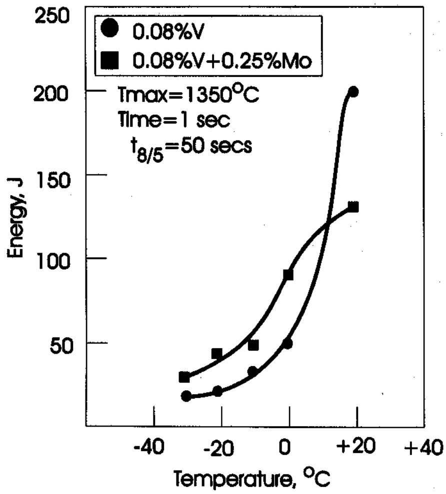


Fig. 12. Charpy Vee Notch Energy Transition Curves of Simulated HAZ's in 0.08%V and 0.08%V+ 0.25%Mo Steels Cooled at 30°C/sec

real welds of approximately the same composition and heat input (5, 6). In the weld simulation the aim is to produce a microstructure which reflects that obtained in the coarse grained HAZ, ie, the worst case. Because the Charpy vee-notch only samples this microstructure the results tend to be low. In a real HAZ, a wider range of microstructures from coarse to relatively fine is obtained and the Charpy notch tends to sample this wider range, resulting in higher apparent toughness levels. This increase in apparent toughness has been shown (7) to result in an improvement in 40J impact transition temperature of 20 - 30°C. Furthermore, comparison of the present results for the 0.08%V steel with those for real welds on similar steels(6), indicates the same level of improvement.

It must reasonably be expected, therefore, that in real welds of the present steels, the energy levels would be higher than obtained in the simulations. In the case of 0.08%V + 0.25%Mo steel, in particular, this can be considered to be very encouraging.

Weld Implant Testing

To obtain an indication of the degree of preheat required to ensure freedom from hydrogen cracking, during field welding, implant testing was carried out on both the 0.08%V and 0.08%V + 0.25%Mo steels rolled by Schedule 3. The electrodes used were 4mm diameter, cellulose based (E 9010G), the heat input was 0.8 - 0.9 kJ/mm, the backing plate was 20mm thick and the applied stress was the yield strength, measured in the longitudinal direction. The level of preheat required to prevent cracking in both steels was 140°C, which is very similar to, but slightly higher than, that of existing X80 steels welded under similar conditions(8). It is also slightly higher than would be predicted from BS 5135, but is significantly below the level which would be predicted in other recent work(10). The reason for the slight increase compared to X80 steels is, undoubtedly, related to the increase in yield strength.

4. CONCLUSIONS

The effects of rolling schedule, finish rolling temperature, cooling rate through the transformation and vanadium level, with and without a molybdenum addition of 0.25%, on the properties of 15mm thick, accelerated cooled, plate of API 5LX100 steel, of base composition 0.08%C/1.85%Mn/0.45%Si/0.05%Nb/Cu, Ni, Ti, have been determined. In addition, an initial assessment of the weldability of steels containing 0.08%V and 0.08%V + 0.25%Mo, has been carried out. It can be concluded that:-

1. Plate of yield strength 100 ksi, with > 170J Charpy vee-notch energy absorption at -20°C and an 85% BDWTT transition temperature <-20°C can be obtained using steel containing at least 0.08%V + 0.25%Mo, rolled by a schedule which included 20 - 21% deformation/pass in the temperature range 850 - 800°C, to finish rolling at a temperature of 800°C and by cooling between 800 and 550°C at a rate exceeding 30°C/sec.

2. Consideration of the 2.0% proof stress indicates that, after U-O-E pipe forming, 100 ksi yield strength should be obtained in pipe containing 0.04-0.06%V + 0.25%Mo, finish rolled at 800°C and cooled at a rate of 25-30°C/sec, between 800 and 550°C.

3. In steels which were rolled with 13 - 21% deformation/pass in the final stages of rolling, reducing the finish rolling temperature from 800°C to 700°C had no significant beneficial influence on tensile or impact properties.

4. Irrespective of rolling conditions, cooling through the transformation had the most significant influence on tensile properties, although it had relatively little effect on impact properties.

5. Increasing the average degree of deformation/pass in the final stages of rolling had the greatest beneficial effect on the impact properties of steels finish rolled at 800°C.

6. The microstructures of the steels were essentially ferrite/bainite in nature and some evidence of relatively coarse Ti-rich and Nb - Ti rich precipitates was found.

7. Simulated weld heat affected zone toughness testing, carried out under conditions which resemble the coarse grained region of a seam weld manufactured at 4kJ/mm, resulted in a 40J impact transition temperature of -20°C, in the case of a steel containing 0.08%V + 0.25%Mo. It can be anticipated that this will improve in a real weld.

8. Weld implant testing, carried out using cellulose based electrodes, indicated that 140°C preheat was required to prevent HAZ hydrogen cracking in this test and this is similar to, but slightly higher than, the temperature required for existing API 5LX80 steels welded under the same conditions.

ACKNOWLEDGEMENTS

The author would like to thank VANITEC who provided the funds and Dr M Keller, of Mannesmann Forschungsinstitut, who carried out the work.

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