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WELD METAL ALLOY SYSTEMS FOR SEAM WELDING OF NIOBIUM MICRO-ALLOYED PIPE STEELS

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Abstract

The mechanical properties of niobium alloyed line pipe steels are achieved during thermomechanical controlled processing (TMCP) and through the formation of niobium carbides and nitrides. More recent developments of higher strength pipe utilize levels of niobium up to 0.11%, achieving exceptional mechanical properties in the presence of additional conventional alloying with elements such as molybdenum and chromium. However, the cooling rates associated with submerged arc welding will not allow the development of the fine grained bainite and ferrite microstructure created during TMCP of the base metal. The weld metal strength and toughness will depend primarily on the influence of alloy concentration upon solidification. Two-run seam welding of pipe often results in 60 percent admixture of the pipe body in the weld metal. The concentration and type of micro-alloying agents introduced from the base metal can have significant effects on weld metal strength, toughness and hardness. In order to achieve the desired balance of weld metal mechanical properties, the alloying additions from the welding consumables are critical.

Introduction

Until recent years, the most common variations of high strength low alloy (HSLA) line pipe steels have relied on Nb and V microalloying. A more recent approach using lower carbon and higher niobium allows X70 and X80 to be more effectively produced using Nb-Cr or Nb-Mo alloying. This technology involves high temperature processing (HTP) to maximize the benefit of niobium, allowing high strength to be developed without undue levels of conventional alloying. In this system, the niobium additions help control the austenite recrystallization grain size. Strength is achieved through precipitation hardening caused by the formation of niobium carbides and nitrides which promote a fine grained microstructure. Coupled with thermomechanical controlled processing and fast cooling rates the niobium additions produce steels with increased strength and improved toughness [1].

Previous screening of weld metal alloy systems indicates that manganese, silicon, molybdenum, titanium and boron influence the properties of pipe seam welds containing niobium. The influence of these elements is further explored in relation to a low carbon X70 pipe body composition containing 0.09 percent niobium and 0.24 percent chromium [1]. The screening also indicated that the concentrations of nitrogen and oxygen influence toughness, in systems containing niobium, in a manner similar to that reported for welds on other pipe body compositions. The influence of these elements will be reported in subsequent publications.

Experimental Procedure

Base Material

The base metal used for this study is a Nb-Cr API X70 pipe steel. The chemical composition can be found in Table I.

Table I. Base Material Chemical Composition

Grade	Thickness	Composition, wt %												
API 5L	mm	C	Mn	Si	S	P	Ni	Cr	Mo	Nb	Ti	Al	Cu	B	V
X70	17.8	0.066	1.52	0.15	0.004	0.01	0.14	0.24	0.01	0.09	0.014	0.046	0.28	<0.0002	0.005

Welding Consumables

To test different weld metal alloy systems, twelve different commercially available electrodes were selected which could be used alone or combined with each other to control resulting weld metal composition.

A flux designed specifically for the manufacture of line pipe was used which has a basicity of 1.3 (Boniszweski basicity index) and is classified as aluminate-basic according to ISO14174.

Joint Configuration and Welding Parameters

The joint and electrode configuration used for this study can be found in Figure 1 and the welding parameters can be found in Table II.

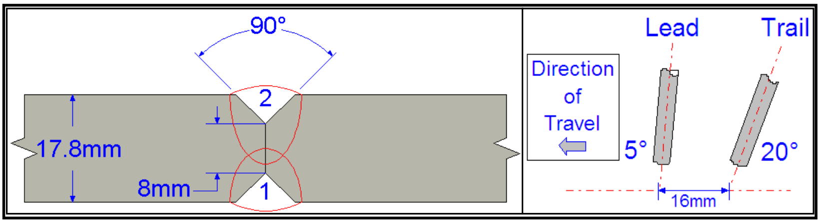

Figure 1. Weld joint and electrode configurations.

Table II. Welding Parameters

Pass/Arc/Polarity	Current (amps)	Voltage (volts)	CTWD (mm)	Travel Speed (cm/min)
1/Lead/DC+	925	29	32	114
1/Trai/AC	650	34	32	
2/Lead/DC+	975	31	32	114
2/Trail/AC	680	36	32	

Mechanical and Chemical Testing

All-weld metal tensile and Charpy V-notch specimens were centered with respect to plate thickness and weld centerline, as shown in Figure 2. Reported impact values are an average of 3 or more impact specimens. Vickers micro-hardness maps consisting of approximately 2000 indents were performed on each weld using a 500 gram force. The chemical compositions of the first and second passes were obtained by Optical Emission Spectroscopy (OES), combustion infrared absorption spectrometry (carbon and sulfur), and inert gas fusion (oxygen and nitrogen).

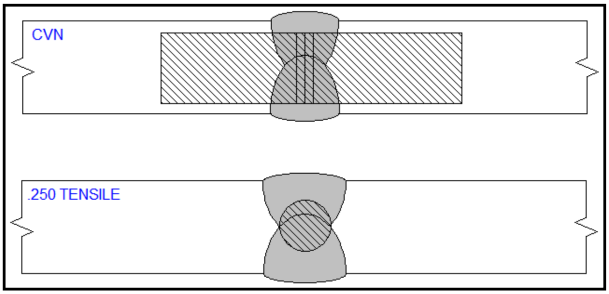

Figure 2. Impact and tensile specimen locations.

Alloy Systems

Manganese and Silicon

Five welds were made with varying levels of manganese and silicon in the deposit. These welds were used as a baseline for testing additional alloying elements in the weld metal. The chemical analysis of each weld can be found in Table III. The mechanical and physical properties together with microstructure and some chemical analysis information can be found in Figures 3-7.

Table III. Chemical Composition for Manganese and Silicon Weld Metal Alloy Systems

Weld #	Chemical Analysis, wt%							
	Analysis Location	C	Mn	Nb	Si	Cu	N	O
1	Weld CL	0.055	1.36	0.052	0.24	0.21	0.008	0.056
2	Weld CL	0.057	1.52	0.053	0.29	0.21	0.008	0.048
3	Weld CL	0.056	1.62	0.054	0.38	0.23	0.009	0.043
4	Weld CL	0.061	1.69	0.055	0.33	0.23	0.008	0.042
5	Weld CL	0.054	1.77	0.054	0.52	0.21	0.008	0.036

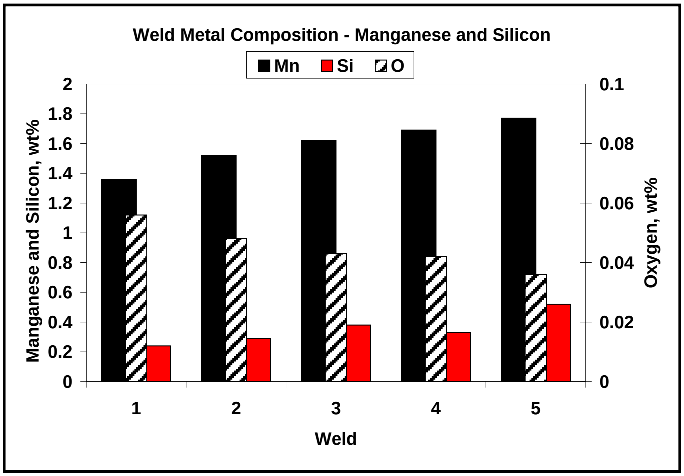

Figure 3. Oxygen concentration at various levels of manganese and silicon.

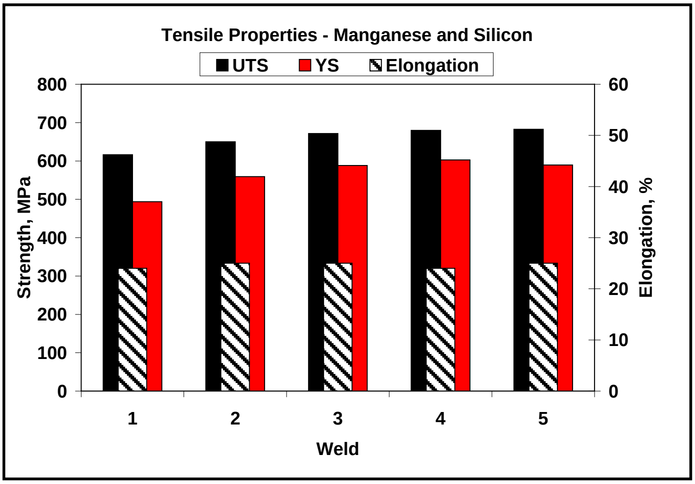

Figure 4. Tensile properties of manganese and silicon weld metal alloy systems.

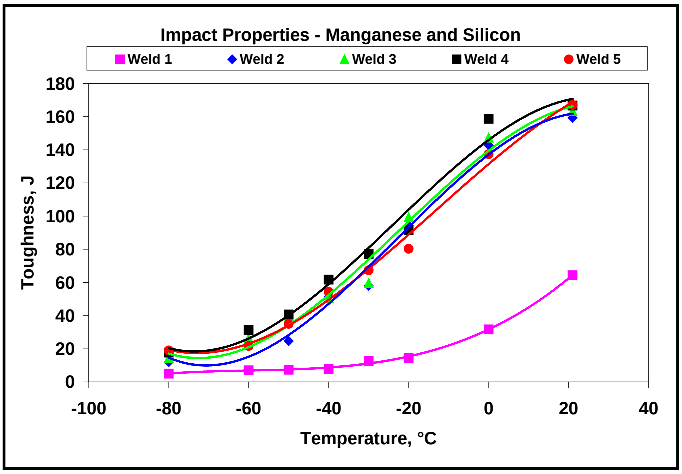

Figure 5. Impact properties of manganese and silicon weld metal alloy systems.

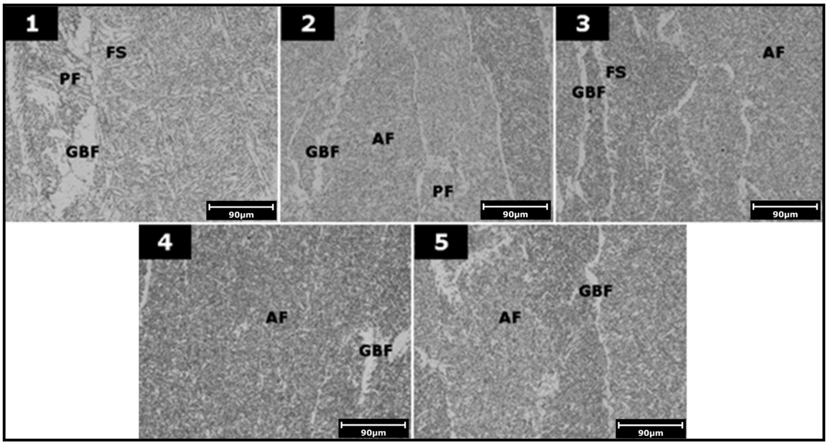

Figure 6. Weld metal microstructure of manganese and silicon weld metal alloy systems.

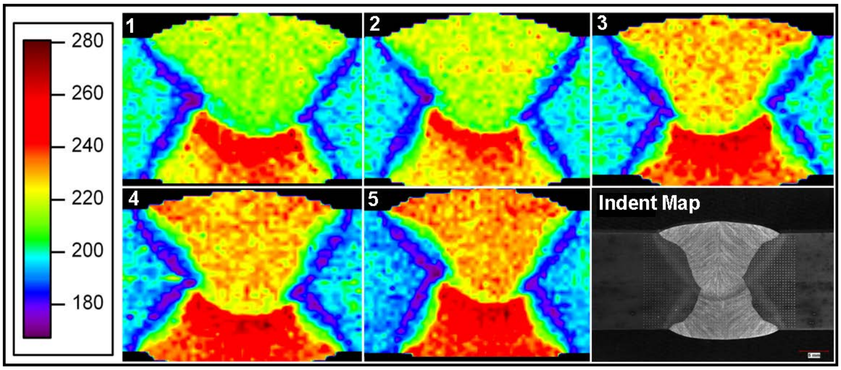

Figure 7. Vickers microhardness maps of manganese and silicon weld metal alloy systems.

Molybdenum

Molybdenum is used to promote the formation of acicular ferrite in the "as deposited" condition. The increase in acicular ferrite formation increases impact toughness. However, when reheated, weld metal containing molybdenum often experiences a decrease in toughness. Reheated regions do not retain their fine grained acicular ferrite microstructure. The microstructure typically transforms into larger grained primary ferrite with an aligned second phase. For this reason molybdenum alloyed electrodes are not typically used for multiple pass welding. For the same reason, a non-molybdenum bearing electrode is often used on the first pass of two-run welds to avoid any negative reheating effects caused by the second pass. However, on thick base material molybdenum is often necessary and beneficial for the first pass since the majority of the weld remains in the as-deposited condition.

To examine the effects of molybdenum, approximately 0.2 percent was added to the mild steel alloy systems of welds 2 and 4. These welds (6 and 8) compare the presence of Mo in medium Mn-Si and high Mn-Si systems. The compositions of the first and second pass for welds 6 and 8 are the same.

To evaluate the effects of reheating molybdenum, welds 7 and 9 have a first pass composition similar to welds 2 and 4 and a second pass composition similar to welds 6 and 8. The chemical composition of the weld metal can be found in Table IV. The result is two groups of electrodes distinguished by the concentration of manganese and silicon. Tensile, impact and hardness properties can be found in Figures 8, 9 and 10.

Table IV. Chemical Composition for Molybdenum Weld Metal Systems

Weld #	Chemical Analysis, wt%								
	Analysis Location	**C**	**Mn**	**Mo**	**Nb**	**Si**	**Cu**	**N**	**O**
2	Weld CL	0.057	1.52	0.01	0.053	0.29	0.21	0.008	0.048
6	Weld CL	0.049	1.5	0.18	0.059	0.29	0.24	0.008	0.058
7	Pass 2	0.052	1.45	0.16	0.053	0.26	0.22	0.010	0.054
	Pass 1	**Similar to Weld #2**							
4	Weld CL	0.061	1.69	0.0	0.055	0.33	0.23	0.008	0.042
8	Weld CL	0.044	1.73	0.16	0.053	0.42	0.24	0.009	0.049
9	Pass 2	0.051	1.76	0.11	0.062	0.42	0.25	0.009	0.048
	Pass 1	**Similar to Weld #4**							

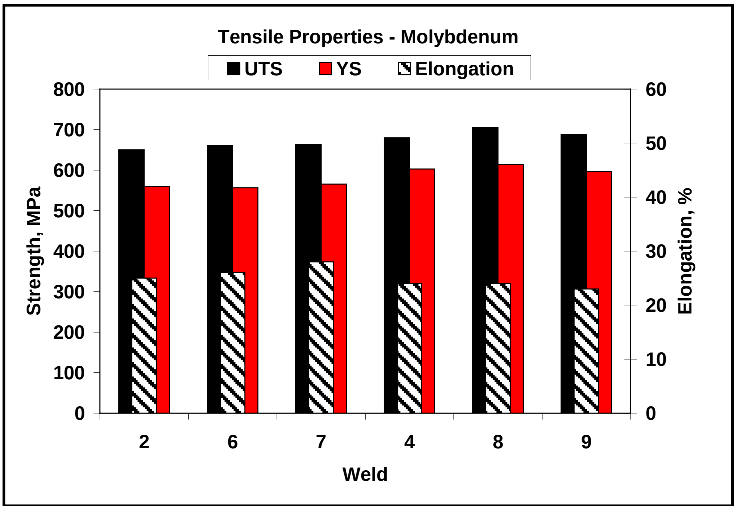

Figure 8. Tensile properties of molybdenum weld metal alloy systems.

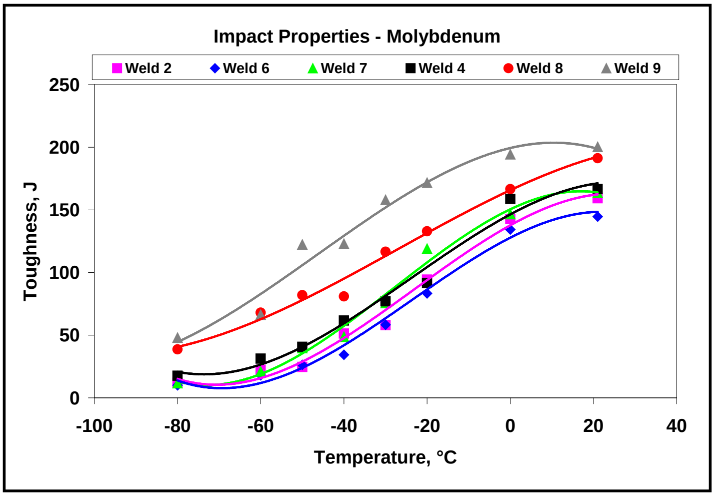

Figure 9. Impact properties of molybdenum weld metal alloy systems.

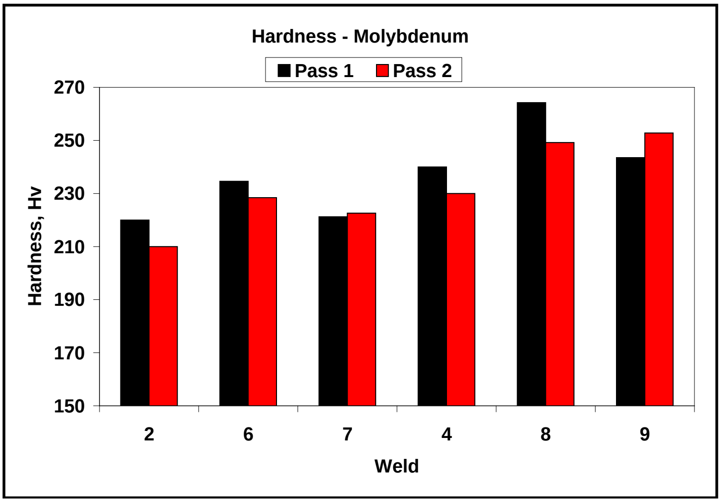

Figure 10. Hardness properties of molybdenum weld metal alloy systems.

Titanium and Boron

Titanium and boron are often added to weld metal systems to increase low temperature toughness. Titanium in small amounts forms inclusions which act as nucleation sites for acicular ferrite. Boron also promotes the formation of acicular ferrite and prevents the formation of larger grain primary, polygonal and Widmanstatten ferrite.

To evaluate the effects of titanium and boron, three welds (10, 11, and 12) were made. Weld metal chemical properties can be found in Table V. Weld 10 isolates the effect of titanium alone. Weld 11 shows the effects of a weld metal system containing both titanium and boron. Weld 12 shows the effects of titanium and boron in combination with molybdenum. To compare the benefits of the three weld alloy systems, the comparable mild steel systems (welds 3, 4, and 6) are included. Graphs of tensile, impact and hardness properties can be found in Figures 11, 12 and 13.

Table V. Chemcial Composition for Titanium and Boron Weld Metal Alloy Systems.

Weld #	Chemical Analysis, wt%									
	Analysis Location	C	Mn	Mo	Nb	Si	Ti	B	N	O
3	Weld CL	0.056	1.62	0.0	0.054	0.38	0.006	ND	0.009	0.043
10	Weld CL	0.058	1.57	0.0	0.055	0.39	0.022	ND	0.008	0.038
4	Weld CL	0.061	1.69	0.0	0.055	0.33	0.006	ND	0.008	0.042
11	Weld CL	0.050	1.69	0.0	0.056	0.34	0.028	0.003	0.008	0.041
6	Weld CL	0.049	1.50	0.18	0.059	0.29	0.00	ND	0.008	0.058
12	Weld CL	0.048	1.54	0.18	0.054	0.33	0.020	0.003	0.008	0.044

(ND: None Detected)

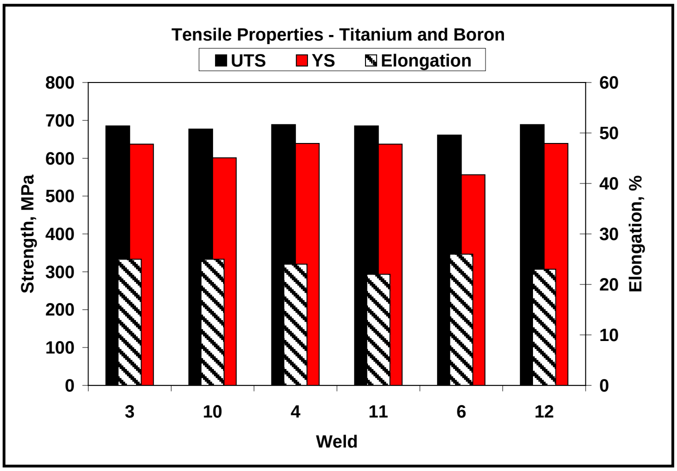

Figure 11. Tensile properties of titanium and boron weld metal systems.

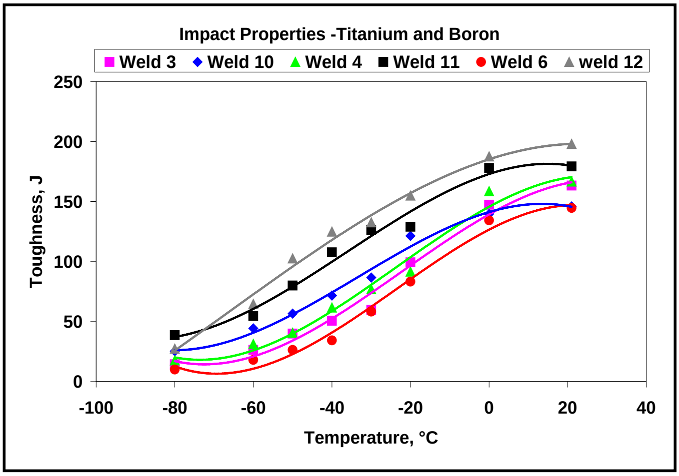

Figure 12. Impact properties for titanium and boron weld metal systems.

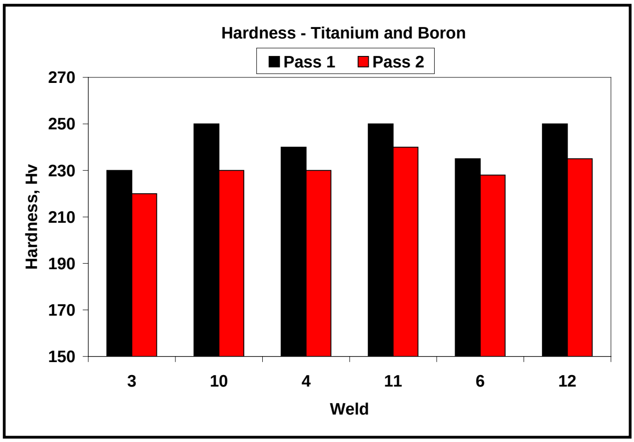

Figure 13. Hardness properties for titanium and boron weld metal systems.

Discussion

Manganese and Silicon

The levels of manganese and silicon in the weld metal are important factors in this system. Increasing the concentration of manganese and silicon decreases the concentration of oxygen in the weld metal as seen in Figure 3. A certain amount of oxygen is needed in two-run welds to form acicular ferrite nucleation sites. The level of oxygen generally needs to be above 300 ppm. Even for the deposit with the highest concentrations of manganese and silicon the oxygen remained above this level.

The influence of manganese and silicon on toughness can be seen from Figures 5 and 6. The inferior toughness of weld 1 compared to weld 2 is suggested to be the result of a low manganese level combined with a high silicon level. The higher manganese level of weld 2 is suggested to be the reason for the appearance of acicular ferrite as shown in Figure 6. Low manganese is often associated with low hardenability and toughness and thus polygonal and or ferrite side plate nucleation. The silicon effect is probably secondary however additional work is required to make definitive statements about its role. The best results were achieved in weld 4 with 1.69 percent manganese and 0.33 percent silicon. The results of weld 5 suggest that further increasing the amount of manganese and silicon is not beneficial and may negatively affect toughness. The decrease in toughness can be attributed to increased hardness and the reduction in volume fraction of acicular ferrite.

Weld metal toughness is directly related to the percentage and coarseness of acicular ferrite (AF) compared to grain boundary ferrite (GBF), polygonal ferrite (PF) and Widmanstatten ferrite (FS). Analysis of the microstructures in Figure 6 indicates that increasing the level of manganese and silicon reduces the amount of proeutectoid GBF, PF, and FS and promotes the formation of fine grain AF.

Increasing the level of manganese and silicon in the weld deposit also increases tensile properties. As seen in Figure 4, ultimate tensile strength (UTS) and yield strength (YS) increase with the amount of these alloys. Increasing manganese levels above 1.7 percent and silicon levels above 0.34 percent does not benefit tensile properties of the weld metal or influence the amount of elongation.

The effect of manganese and silicon on hardness can be seen in the hardness maps included in Figure 7. Increasing manganese and silicon yields an increase in the hardness of both the refined weld metal of the first pass and the as-deposited weld metal of pass two.

Molybdenum

For the medium Mn-Si system, comparing welds 6 and 2 shows little increase in weld metal tensile properties, no increase in toughness, and a significant increase in hardness. Removing Mo from the first pass (weld 7) eliminates the negative effects of reheating weld metal containing molybdenum. Comparing welds 7 and 2, shows increased toughness and a less significant increase in first pass hardness when adding molybdenum to the second pass only.

For the high Mn-Si system, comparing welds 8 and 4 shows little increase in weld metal tensile properties, a significant increase in toughness and a significant increase in hardness. Weld 9, in which Mo is removed from the first pass of the high Mn-Si system, yields similar effects to the same change in the medium Mn-Si system. Again, the increase in first pass hardness is minimized and the tensile strength is essentially unchanged. In this case, the increase in toughness is very significant.

Titanium and Boron

The addition of titanium (weld 10) to the high manganese and medium silicon system of weld 3 exhibits slightly increased toughness at low testing temperatures. The addition of titanium appears to increase hardness without any influence on tensile properties.

Adding titanium and boron (weld 11) to the high manganese and medium silicon system of weld 4 yields a much more significant increase in toughness than experienced with the addition of titanium alone. Similarly, the addition of titanium and boron do not influence weld metal tensile properties but again yield an increase in hardness.

The addition of titanium and boron (weld 12) to the high manganese and medium silicon system containing molybdenum (weld 6) yields the best impact properties with a slight increase in yield strength and an increase in hardness.

Conclusions

The following conclusions can be made based on the data collected from this research concerning the performance of various weld metal alloy systems for the welding of this 0.09 percent niobium micro-alloyed X70 pipe steel.

1. High strength and toughness can be achieved in weld metal containing 0.055 percent niobium, with the proper balance of manganese, silicon, molybdenum, titanium and boron.
2. In weld metal systems containing only manganese and silicon, optimum toughness appears to be obtained in alloys which contain approximately 1.5 percent manganese and 0.3 percent silicon. Higher or lower levels of these elements are likely to significantly reduce the level of weld metal toughness. A deterioration in toughness was observed at the highest levels of manganese and silicon examined. This was attributed to a reduction in the proportion of acicular ferrite in the microstructure and to an increase in hardness.
3. A high concentration of silicon in two-run mild steel weld deposits may negatively affect weld metal mechanical properties and microstructure.
4. The addition of approximately 0.2 percent molybdenum to as-deposited weld metal is an effective way to increase toughness, particularly with higher concentrations of manganese and silicon up to approximately 1.7 percent manganese and 0.45 percent silicon.
5. Titanium and titanium-boron weld metal systems exhibit increased toughness compared to mild steel deposits with the same levels of manganese and silicon.
6. Titanium and boron when combined with molybdenum produce the best impact properties.
7. Increasing the amount of manganese, silicon, molybdenum, titanium and titanium-boron in reheated and as-deposited weld metal systems results in increased hardness.

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