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ORIGINAL ARTICLE

Influence of the chemical composition of weld electrode on the mechanical properties of submerged arc welded pipe

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Abstract Submerged arc welding (SAW) is extensively used in pipe production. Because of the need for high toughness in a pipeline, it is necessary to develop wires and fluxes for high-efficiency SAW to produce weld metal (WM). Investigations are carried out in real spiral pipe production factory by the multi-wire double seam SAW process using constant welding parameters and the same flux. Two different chemical compositions of API-X65 steel and four different chemical compositions of weld electrodes have been used in this investigation to evaluate the effect of WM chemical composition on the mechanical behaviour of welded X65 steels. Vickers hardness, Charpy V-notch (CVN) impact toughness and tensile strength tests have been conducted. The toughness of the WM is lower than BM and HAZ. The WM toughness improvement depends on the weld electrode that is used and increases with increasing Mn content of the weld electrode used. The weld electrode contains B and Ti micro-alloy elements that can produce high toughness WM. The mechanical properties of WM are changed by using different weld electrodes. This work shows the importance of the selection of weld electrode composition in order to improve the mechanical properties of steel welds.

Keywords Submerged arc welding (SAW) · Weld electrode · Weld metal · Mechanical properties

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1 Introduction

In the submerged arc welding (SAW) process, arc formation occurs between a continuously fed weld electrode and the work piece [1]. Both the weld electrode and the base metal are melted beneath a layer of flux to form the weld bead [1, 2]. Because of the easy process control, high deposition rate, time savings, reduced cost, excellent surface appearance, invisible arc, lower welder skill requirement, improved repair procedure and increased efficiency and productivity, the submerged arc welding process is widely used in the production of pressure vessels, marine vessels, pipelines and offshore structures [3, 4]. The main variables in the SAW process can be described as weld electrode, flux and welding parameters [5]. The welding parameters of SAW are current, polarity, voltage, weld groove, travel speed, distance between electrodes, electrode extension, angle and diameter [3, 4]. High productivity and cost effectiveness can be obtained with an optimal selection of input parameters [4, 6].

The strength–toughness combination is expected to be excellent for pipeline technology. Therefore, the microstructure of the steel must maintain the optimum strength–toughness combination. In addition, a severe running environment, such as earthquakes, landslides and debris flows, is inevitable for long-distance pipelines. Therefore, pipeline steels must also have a high deformability characteristic [7]. Oil and gas transmitting steel pipelines should have additional requirements such as weldability, formability, low ductile to brittle transition temperature, fracture toughness, resistance to hydrogen-induced cracking in a sour service environment, stress corrosion-cracking resistance for underground service, especially in a H_2S environment and fatigue resistance [2, 8, 9]. To develop the transportation performance that is required in high-pressure operation and to decrease pipe installation costs, high-strength low-alloy (HSLA) micro-alloyed steel pipes are being used to transport oil and natural gas [2, 8]. The alloy chemistry, thermo-mechanical processing and degree of cooling determine the microstructure. It is generally preferred that pipeline steels have an acicular ferrite microstructure [9].

The base metal (BM), the heat-affected zone (HAZ) and the weld metal (WM) are parts of the welded joint and define the service properties of the welded pipe [10]. The WM of SAW is produced by a chemical and physical reaction of the weld electrode, the base metal and the flux [10] and the alloying elements coming from them [4, 11, 12]. Weld electrodes and fluxes should be developed to provide a WM and BM match [10, 11]. The chemical compositions of the weld electrode are designed to obtain a WM mainly consisting of acicular ferrite and increase the strength and toughness of weld metal by adding micro-alloying elements. The weld electrode and obtained hardness of the WM should have an acceptable hardness [10]. The microstructure and micro-hardness values of the WM and HAZ are used to predict the mechanical properties of a weldment such as strength and toughness [4]. To continuously obtain better mechanical properties, the control of WM chemical composition is becoming more crucial for safety in welded structures [4]. Multiple combination possibilities of weld electrodes and fluxes that are allowed by SAW help to classify and match specific applications [1, 10]. Because the chemical and physical properties of WM and BM can be matched with each other, the SAW process is preferred.

The decrease in Charpy V-notch (CVN) impact toughness with increasing tensile strength of a structural steel WM is a well-known subject. However, both the strength and toughness of a WM can be increased by grain refinement [12]. According to the welding process and the cooling rate, typical microstructures of mild steel BM and HAZ consist of grain boundary ferrite, widmanstatten ferrite, fine pearlite, banite, acicular ferrite, equiaxial ferrite and martensite [4, 11]. Because the fine size structure of acicular ferrite has a higher resistance to crack propagation, it may provide good toughness and tensile strength to the welds. Impact properties can be improved by maximising the amount of acicular ferrite, minimising the amount of grain boundary ferrite and controlling the size, shape and level of inclusions [10–14]. Hence, increasing the volume fraction of acicular ferrite in welds is suitable, but increasing beyond a certain volume fraction of acicular ferrite, the toughness decreases. Consequently, a good toughness value is obtained with a high enough proportion of acicular ferrite and by ensuring the least amount of martensite [15].

Fine and uniformly distributed inclusion particles in weld metal can promote the formation of acicular ferrite and improve the toughness of the weld metal. Elemental contents of titanium (Ti), boron (B), manganese (Mn), vanadium (V), silicon (Si), aluminium (A1), calcium (Ca), nitrogen (N), oxygen (O) and nickel (Ni) strongly influence the toughness [10, 12, 16]. There are two major methods to increase the toughness of the WM. While the first major method is to change the WM composition either through the use of filler metals or by metal powder additions in the WM, the second method is to use different types of fluxes [16–20]. Since the difference in the volume fraction of WM acicular ferrite affects the toughness [10, 11, 13], acicular ferrite formation is promoted.

Ti, under certain alloying conditions, can have a positive influence on the structure and toughness of HAZ, particularly when welding with high heat inputs. The effect brought about by Ti is partly because of the fact that the extremely fine titanium nitride precipitates and fine titanium oxide particles that are produced at the steelmaking stage hinder grain growth to a certain extent [10–12, 14, 17, 21]. The effect of Ti on SAW metals has been investigated and it has been concluded that, ferrite veining occurs and toughness deteriorates with increasing Ti content; however, at a certain level, Ti substantially increases toughness. While Ti has a strong effect on microstructural evolution and development of mechanical properties in HSLA steel WM, it also shows a strong interaction with other alloying elements. The usage of a combination of high Mn and low Ti suppresses formation of ferrite veining, and this suppression can increase impact toughness [22]. The interaction of Ti and B and its effects have also been investigated by Mori et al. and Evans, and it is noted by Wang and Liu [12] that B atoms placed in austenite grain boundaries of the weld metal delay nucleation of proeutectoid ferrite, therefore enabling suitable conditions for acicular ferrite nucleation [10, 12, 14]. While Ti serves to protect B from O and N, with B, it is also effective in maximising acicular ferrite formation [12]. They also stated that the maximum amount of acicular ferrit occurs at lower B content for different Ti level; thus considering impact toughness, there should be an optimum combination of Ti and B elements [12]. Therefore, an electrode containing Ti and B is used to improve toughness [14].

The microstructural distribution in a weld metal is considerably affected by the content of Si or Mn [12]. Since the increased amount of Si reduces the ductility and makes brittle the welding connection, Si content should be below 0.5 wt.% in low-alloy steels [12, 22]. Weld electrodes containing Mo are used to promote acicular ferrite in the weld deposit. Mo

Table 1 The chemical composition of API-X65 steels (wt.%) together with target values specified by API 5L

Material	Element (wt.%)														
	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	N	Nb	Ti	V	CE (Pcm)
Type I-X65	0.040	0.18	1.07	0.012	0.001	0.015	0.003	0.234	0.040	0.012	0.0065	0.052	0.0021	0.055	0.110
Type II-X65	0.035	0.22	1.32	0.007	0.001	0.005	0.054	0.192	0.031	0.127	0.0040	0.053	0.0193	0.059	0.128
API 5L X65	0.220	–	1.45	0.025	0.015	–	–	–	–	–	–	–	0.0600	–	0.250

additions of up to 0.4 wt.% can be used to increase the percentage of acicular ferrite, and its use will be limited by weld hardness limitations [14]. An increase in Mn content in weld metals with Mo additions firstly increases the toughness and then, after a certain point, reduces the toughness. In addition, if the Mo amount increased significantly, excellent properties of weld metals in highly alloyed steel are achieved [16]. The usage of Mo and Ni together results in hardening the WM and decreases the impact toughness. With the addition of Mo and Ni alloying elements, the amount of ferrite veining decreases while acicular ferrite increases. It is also found that an improvement in impact toughness occurs when Mo and Ni are introduced in weld metals [16, 22]. V is useful to the precipitation strengthening of weld metal [10].

Investigations are carried out employing real line-pipe spiral welds that are produced by the multi-wire double seam submerged arc welding process. The X65 pipes are produced by constant welding parameters, using the same flux and different weld electrodes to determine the effect of the weld electrode on the chemical composition of WM and mechanical properties of welded X65 steels. Also, the effect of minor differences in chemical composition of base metal is studied by using two types X65.

2 Materials and experimental procedure

The pipes under study in this research have an 846-mm outer diameter and an 8.74-mm-thick wall and are made of an API-X65 steel strip. Two different chemical compositions of API-X65 steel were used in this investigation to determine the effect of minor differences in the base metal on mechanical behaviour. They were named type I-X65 and type II-X65. The chemical analyses of base materials were determined by optical emission spectroscopy. The carbon equivalent is calculated using the following formula CE (Pcm) (Eq. 1) because the carbon (C) content is less than 0.12 %. The measured chemical composition and the equivalent carbon, calculated by Eq. 1, are given in Table 1, together with the target values for the test material specified by API 5L [23]. Where, C, Si, Mn, B, Cr, Ni, Mo, V and copper (Cu) represent the metallic content, expressed as percentages. Table 1 shows that all measured element values are below or close to the maximum values of the API 5L specification.

$$CE(P_{cm}) = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5B \quad (1)$$

The pipes were manufactured by spiral forming. The steel was uncoiled, levelled and passed through a forming station that spirals the steel to the required outside diameter. The spiral pipe was double-side welded, both internally and externally, employing the highly efficient multi-wire double seam submerged arc process. The external weld seam (outer weld) was conducted following 1/2 tour rotation of pipe after the internal weld seam (inner weld). Schematic illustration of internal and external weld heads for SAW of the spiral pipeline and obtained weld seam form after the use of each weld head are given in Fig. 1 [24]. Two electrodes were used for each side of the pipes. While the direct current (DC) power source was used for the first electrode to ensure high penetration, the alternative current (AC) power source was used for the later electrode to prevent arc blow. The steel pipe was cut to the required length to travel out of the forming and welding machine. The weld was allowed to cool in air. Spiral steel pipes

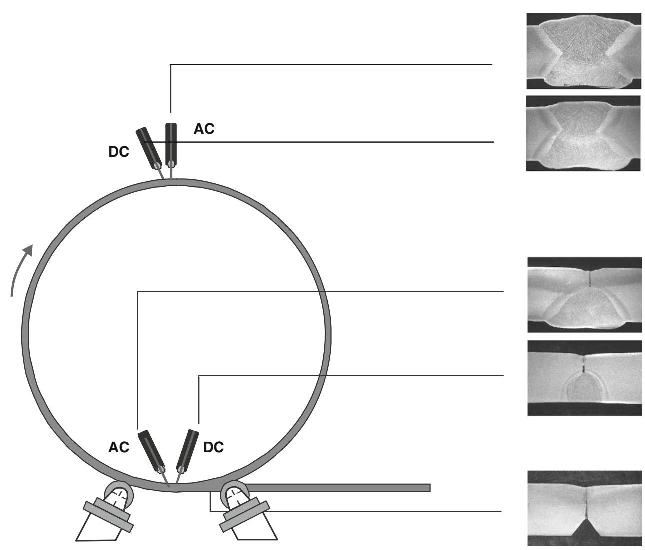

Fig. 1 Schematic of internal and external weld heads for SAW of a spiral pipeline

Table 2 The chemical composition of weld electrodes (wt.%)

Electrode	Element (wt.%)												
	C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Al	V	Ti	B
S2Mo	0.11	0.89	0.16	0.010	0.010	0.04	0.04	0.50	0.02	0.010	0.01	–	–
S3Mo	0.10	1.62	0.15	0.010	0.010	0.05	0.04	0.49	0.04	0.006	0.01	–	–
S4Mo	0.11	1.85	0.15	0.010	0.010	0.06	0.05	0.51	0.04	0.006	0.01	–	–
S3MoTiB	0.07	1.27	0.29	0.010	0.010	0.04	0.03	0.51	0.03	0.004	0.01	0.15	0.013

were produced according to API 5L specification and were carefully tested using a hydrostatic test, a dimensional test, a surface inspection, a visual inspection and a non-destructive inspection; thus, high quality and reliability of the delivered pipes were guaranteed.

The type I-X65 and type II-X65 pipes were produced by the multi-wire double seam submerged arc welding technique by constant welding parameters, such as current, voltage and welding speed using the same flux and different weld electrodes to explain the effect of alloying elements in the weld electrode. The chemical compositions of the weld electrodes and flux used are shown in Tables 2 and 3, respectively.

Multi-wire double seam submerged arc welding was applied using four different weld electrodes. The details of the welding technique and weld electrode specifications are given in Table 4. The approximations of the heat input per unit length of the weld bead (HI) were determined using Eqs. (2), where: HI = heat input per unit length of weld bead (J mm^{-1}), E = arc voltage (V), I = welding current (A), S = welding speed (mm s^{-1}) and f_1 = arc efficiency = 0.99, which was the mean of the range of values reported for the SAW process [25]. As shown in Table 4, the heat input was the same for all applications at each weld bead. While the first pass of internal and external weld seams were done using different welding electrodes, the second pass of internal and external weld seams were done using only S2Mo electrodes. The measured chemical composition of weld metals and calculated Ces values are given in Table 5 for each condition.

$$HI = f1 \frac{I \times E}{S} \tag{2}$$

To measure the tensile properties of type I-X65 and type II-X65 base metals, six flat tensile bars were taken from the original pipe in its hoop direction as suggested by the API 5L specification and prepared according to the EN 10002 standard [26]. The samples used in the tensile tests for the evaluation of the tensile properties of welded type I-X65 and type II-X65 consist entirely of WM. All tests were carried out at room temperature under a low displacement rate. The obtained average mechanical properties of type I-X65 and type II-X65 base metal are shown in Table 6 together with the target values specified by API 5L [23]. While the tensile strengths and elongation percentages of the weld metals are given in Table 7, the yield strengths are not shown because they were not defined because of a sudden rupture in the weld metal.

Because hardness is a significant parameter for the assessment of cold cracking resistance, the strength, ductility and toughness as well as the hardness of the BM, HAZ, and WM were determined using a Future-Tech micro-hardness tester with a load of 200 g. Micro-hardness measurements were made in a straight line 1.5 mm below and parallel to both the surface and the middle of the BM plate to cover the complete WM, HAZ, and a part of the BM. Figure 2 shows the configuration of the weldment cross-section on which the hardness measurement was conducted. The measured hardness data and obtained average hardness values are given in Table 8. All measured hardness data fall in the range of 174 to 221 HV, meeting the maximum hardness limitation of 350 HV and fulfilling the API 5L specification.

Charpy V-notch (CVN) impact tests were conducted on six samples for each condition. All 2/3 size test specimens with a size of 6.67 × 10 × 55 were prepared according to the DIN 50115 standard [27]. While the CVN impact test specimens were taken from BM, WM and HAZ for weld samples A and E, the CVN impact test specimens were taken only from BM and WM for weld samples B, C and D at −20 °C, as shown in Table 9. While CVN impact tests of weld samples B, C, D and E were conducted at only −20 °C, tests of weld sample A were conducted at five different temperatures, namely −60, −40, −20, 0 and 20 °C, as shown in Table 10.

Table 3 The chemical composition of flux (wt.%)

Flux composition (wt.%)	SiO_2	MnO	MgO	CaF_2	NaO	Al_2O_3	CaO	TiO_2	K_2O	FeO	Metal alloys
Lincolnweld P223	23	4	21	21	2	20	4	2	1	1	3 max

Table 4 Details of welding technique including number of wires and weld passes, current, voltage, heat input and speed

Pipe size (mm)	Pipe material	Weld sample	Weld position	Weld electrode number	Weld electrode	Wire diameter (mm)	Polarity	Welding current (A)	Arc voltage (V)	Heat Input (J/mm)	Welding speed (m/min)
864*8.74	Type I-X65	A	Internal weld	1 2	S2Mo S2Mo	3.2 3.2	DC AC	775 550	29 29	1048	2.20
			External weld	1 2	S2Mo S2Mo	3.2 3.2	DC AC	725 450	29 29	929	
		B	Internal weld	1 2	S3Mo S2Mo	3.2 3.2	DC AC	775 550	29 29	1048	2.20
			External weld	1 2	S3Mo S2Mo	3.2 3.2	DC AC	725 450	29 29	929	
		C	Internal weld	1 2	S4Mo S2Mo	3.2 3.2	DC AC	775 550	29 29	1048	2.20
			External weld	1 2	S4Mo S2Mo	3.2 3.2	DC AC	725 450	29 29	929	
		D	Internal weld	1 2	S3MoTiB S2Mo	3.2 3.2	DC AC	775 550	29 29	1048	2.20
			External weld	1 2	S3MoTiB S2Mo	3.2 3.2	DC AC	725 450	29 29	929	
	Type II-X65	E	Internal weld	1 2	S2Mo S2Mo	3.2 3.2	DC AC	775 550	29 29	1048	2.20
			External weld	1 2	S2Mo S2Mo	3.2 3.2	DC AC	725 450	29 29	929	

For some chosen samples, optical micrographs were taken. Mounting, grinding, polishing, and etching of test specimens in 2 % nital solution were performed to reveal and analyse the microstructure of the BM, WM and HAZ regions with an optical microscope. The double weld seam, heat-affected zone and base metal next to the weld seam are clearly displayed in the macroscopic image of the welded joint as shown in Fig. 3 for weld sample A. The weld bead dimensions were measured from the transverse section of each weld specimen using an optical microscope. The weld bead width was measured as the width of the fusion zone on the top surface of the base plate. The penetration was measured as the depth of the fusion zone from the top surface of the base plate. The reinforcement height was measured as the height of the weld deposition above the top surface of the base plate [28]. The maximum and minimum values of weld bead widths, reinforcement heights and penetrations are given in Table 11 for type I-X65 and type II-X65 steels. The microstructures of BM, WM and HAZ were not examined and which phases were included was not determined.

3 Results and discussion

As shown in Table 1, the type I-X65 and type II-X65 steels are low C (0.040 and 0.035 wt.%, respectively) steels, containing Ti, V and niobium (Nb) as basic micro-alloying and precipitate hardening elements. These micro-alloying elements provide a good combination of strength and toughness. The very low S content (0.001 wt.%), the higher amounts of Si (0.18 and 0.22 wt.% for type I-X65 and type II-X65, respectively) and Al (0.040 and 0.031 wt.% for type I-X65 and type II-X65, respectively) additions are evidence of clean steel production.

Table 5 The chemical composition of weld metals and calculated CE value (wt.%)

Weld sample	Element (wt.%)													
	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	N	Nb	Ti	V	CE (Pcm)
A	0.046	0.25	1.16	0.008	0.002	0.021	0.165	0.171	0.016	0.03	0.005	0.037	0.0028	0.044	0.133
B	0.048	0.24	1.31	0.008	0.002	0.021	0.162	0.171	0.016	0.03	0.006	0.037	0.0029	0.044	0.142
C	0.050	0.24	1.35	0.008	0.002	0.029	0.162	0.188	0.016	0.05	0.0055	0.036	0.0029	0.044	0.147
D	0.044	0.28	1.26	0.010	0.002	0.025	0.171	0.168	0.016	0.04	0.006	0.037	0.0265	0.045	0.138
E	0.039	0.28	1.32	0.003	0.002	0.010	0.215	0.140	0.010	0.11	0.005	0.034	0.0070	0.040	0.141

Table 6 Mechanical properties of type I-X65 and type II-X65 base metal and target values specified by API 5L

API grade	Dimension			Mechanical properties			
	Outside diameter *D* (mm)	Wall thickness *t* (mm)	*D*/*t*	Yield strength YS (Mpa)	Tensile strength TS (Mpa)	YS/TS	Elongation (%)
Type I-X65	846	8.74	96.8	503	587	0.856	34
Type II-X65				506	586	0.863	33
API 5L-X65 (min-max)				448–600	531–758		

Because the flux used was the same for all of the applications, the differences in the chemical composition of the weld metal mainly depended on the welding electrode used. There was no Nb in the weld electrodes. While V was found in all of the weld electrodes used, Ti and B were only found in the S3MoTiB weld electrode. Comparing Table 1 with Table 5, the difference in chemical compositions between weld metal and base metal can be seen. Since the base metal is melted to obtain the weld metal, the weld metals contain base metal Nb in an amount of approximately 71 and 64 % corresponding to 0.037 and 0.034 wt.% Nb for all weld samples of type I-X65 (A, B, C, D) and type II-X65 (E), respectively. Nb content is beneficial to the precipitation strengthening of weld metal.

As shown in Tables 2 and 5, V content of the weld metals is much higher than those in the weld electrode because the dilution by the base metal includes more V (wt.%). Since V content of the used weld electrode is lower than V content of the base material, V content of the obtained weld metal is lower than the base material, higher than the weld electrode. The V contents of base metal, weld electrode and weld metal are 0.055, 0.010 and 0.044 wt.%, respectively, for type I-X65 weld samples A, B, C and D. The values for type II-X65 weld sample E are 0.059, 0.010 and 0.040 wt.%, respectively.

The Ti content of the weld metal changed depending on the electrode used. When type I-X65 includes 0.0021 wt.% Ti is welded both internally and externally with S2Mo + S2MO or S3Mo + S2Mo or S4Mo + S2Mo weld electrodes which do not contain Ti (weld samples A, B and C respectively); the Ti content of the weld metal is 0.0028 wt.% with approximately a 35 % increase. The increase in the Ti content is most likely a result of the flux used. When type I-X65 is welded with a S3MoTiB electrode inside of a S2Mo electrode as the first electrode at the inner and outer weld seams, the Ti content of the weld metal increases from 0.0028 to 0.0265 wt.% for weld samples A and D, respectively. It can be noted that the amount of Ti in the weld metal increases with the existence of Ti in the weld electrode. The Ti content in the weld metal is only approximately 18 % of that in the weld electrode for weld sample D because of dilution and oxidation. The S3MoTiB weld electrode contains 0.013 wt.%B, but the amount of B in the weld metal is not measured in weld sample D.

Table 7 Mechanical properties of weld samples A, B, C, D and E

Pipe material	Weld sample	Tensile properties	
		TS (Mpa)	Elongation (%)
Type I-X65	A	607	21
	B	592	21
	C	589	19
	D	597	19
Type II-X65	E	611	22

Although Mo is a stable element, the contents of Mo in weld metals are much lower than those in the weld electrodes because of the dilution by the base material. Because the used base material and the weld electrode are the same, the Mo content in weld metals is almost the same for weld samples A, B, C and D. While the Mo content of the base material is increased from 0.003 to 0.054 wt.% by using type II-X65 instead of type I-X65, the Mo content of the WM is increased from 0.165 wt.% (weld sample A) to 0.215 wt.% (weld sample E). The Mo content shows a tendency to increase with increasing the content of that element in the base metal, but it is limited. A 30 % increase in Mo content in the WM is obtained with an 18-fold increase in Mo content in the base material.

The C, Mn and Si contents of WM also show a tendency to increase considering the base material. The C content of WM shows a tendency to increase with an increase in the content of that element in the weld electrode. Because the chemical composition of WM not only depends on the weld electrode but also on the flux, some of this increase is a result of the used flux, as in the Si content. Although the Si content of the weld electrode is lower than that of the base metal, the Si content of the weld metal increases because of the used flux. Changing

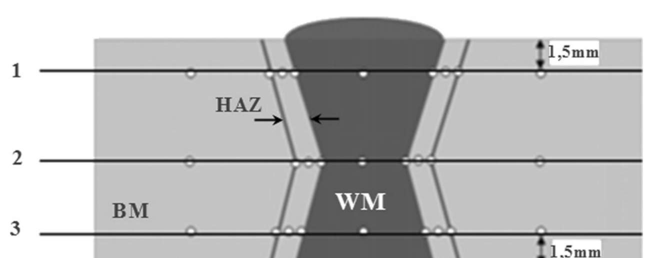

Fig. 2 Schematic of weldment cross-section and hardness measurement

Table 8 Measured and average hardness data of weld samples A, B, C, D and E

Weld sample	Hardness (Hv)			
	Position	Base metal	Heat-affected zone	Weld metal
A	I	180	194	215
	II	182	194	208
	III	183	196	221
A average		182	195	215
B	I	187	205	215
	II	187	201	213
	III	189	199	218
B average		188	202	215
C	I	182	193	205
	II	181	191	201
	III	187	199	213
C average		183	194	206
D	I	178	199	206
	II	180	197	209
	III	176	191	221
D average		178	196	212
E	I	174	189	206
	II	178	192	193
	III	177	194	195
E average		176	192	198

the content of Si can dramatically affect the microstructural distribution in a WM. The increasing amount of Si reduces the ductility, and the welding connection is brittle.

With a general approach, the weld metal content depends on the weld electrode and flux used. The measured 0.133–0.147 wt.% carbon equivalents (CE) of weld metal are far below the maximum value of 0.250 wt.% that is limited by the API 5L specification. This is required to enhance the weldability of the pipe material. Comparing the CE % in weld metal and base metal also shows that CE % increases in weld metal, as observed in Tables 1 and 5. Increasing the CE % increases the volume fraction of low-temperature products and the production of a fine microstructure [2].

The yield strength, tensile strength and elongation % data obtained for type I-X65 and type II-X65 steels are summarised in Table 6. While the yield strengths of type I-X65 and type II-X65 are 503 and 506 MPa, the tensile strengths of type I-X65 and type II-X65 are 587 and 586 MPa, respectively. The measured yield strengths and tensile strengths for tested steel fulfil the API 5L specification. Another important parameter for pipe steels is their yield to tensile ratio. This parameter is an indication of pipe capacity to strain hardening and should be less than 0.93 for X60 and greater pipe steels. The measured yield to tensile ratios for type I-X65 and type II-X65 steel are 0.856 and 0.863, respectively. The tensile strength and elongation % of the weld metal for type I-X65 and type II-X65 pipe steels are given in Table 7. The tensile strengths and elongation % of the weld metal for type I-X65 pipe steels are different for weld samples A, B, C and D because different weld electrodes were used and different weld metals were obtained. Contrary to expectations, tensile strength decreases with the increase in carbon equivalents. For instance, the tensile strength decreases from 607 to 589 MPa with the increase in CE from 0.133 to 0.147 wt.% for weld samples A and C.

The measured hardness data and obtained average hardness values are shown in Table 8. The average hardness remains nearly constant at 182 and 176 Hv levels in the base metal for type I-X65 and type II-X65, respectively. The average hardness of the weld metal is between 206 and 215 Hv, which is slightly higher than the hardness of the base metal for type I-X65. The hardness of the weld metal is 198 Hv, which is slightly higher than the hardness of the base metal for type

Table 9 CVN impact energy of weld samples A, B, C, D and E at −20 °C

Charpy test specimen	Charpy fracture energy (J) at −20 °C				
	A	B	C	D	E
Base metal	167				191
Weld metal	80	123	128	144	88
HAZ	127	–	–	–	147

Table 10 CVN impact energy of weld sample A conducted at -60, -40, -20, 0 and 20 °C

Charpy test sample A	Charpy fracture energy (J) at				
	−60 °C	−40 °C	−20 °C	0 °C	20 °C
Base metal	166	163	167	175	174
HAZ	122	124	127	141	129
Weld metal	16	32	80	102	131

Fig. 3 The macrostructure of the welded joint for weld sample A

Table 11 Weld bead geometry of type I-X65 and type II-X65 steels

Pipe size (mm)	Pipe material	Location	Reinforcement height max.-min (mm)	Bead width max.-min (mm)	Penetration max.-min (mm)
864*8.74	Type I-X65	Internal weld	1.4–1.6	10.3–10.6	5.2–5.8
		External weld	1.6–1.8	12.1–12.4	4.4–4.8
	Type II-X65	Internal weld	1.2–1.4	11.1–11.5	5.0–4.6
		External weld	1.6–1.8	12.5–12.9	4.4–4.8

II-X65. While the maximum hardness is obtained in the weld metal, the minimum hardness is measured in the base metal for all applications. This can be attributed to the increased CE value and the presence of lower temperature transformation products (e.g. bainite, widmanstatten ferrite) in the weld metal, but these were not researched in this work. When weld samples A and D are compared, it can be noted that the ultimate tensile strengths and the elongation percentages, as well as the Vickers hardness of weld metal, decrease with an increase in the titanium content in the weld metal. This finding can be attributed to the amount of pearlite percentage in the welds but it wasn't determined in this work. As known that, an increase in the Ti content of WM reduces the ultimate tensile strengths, the elongation percentages, the Vickers hardness and the amount of pearlite in the WM. In contrast, the toughness increases with the titanium content in the welds, and it can be related to the higher acicular ferrite percentages formed in the welds but it was not determined in this work.

Table 9 shows the energy value of the CVN impact test for the BM, HAZ and WM of type I-X65 and type II-X65 steel pipes at −20 °C. While the CVN impact toughness of the base metal is increased from 167 to 191 MPa, the CVN impact toughness of the weld metal welded at the same conditions is increased from 80 to 88 MPa by using type II-X65 instead of type I-X65. The influence of the used base metal on the toughness of welded structures is clearly seen. The measured CVN impact toughness from three different zones is well above the minimum required value of 73 J which is determined by the API 5L specification. Table 9 shows the influence of the used electrode on the toughness of welded type I-X65 structures. Considering samples A and B, the measured weld metal CVN impact toughness increases from 80 to 123 J with an increase in the Mn content in the weld metal from 1.16 to 1.31 wt.% (Table 5), depending on the weld electrode that was used. The obtained improvement in the CVN impact toughness is 54 %. Because Mn is an important alloying element for solid solution strengthening and deoxidization, changing the content of it can dramatically affect the microstructural distribution in a weld metal. Considering sample C, a similar improvement of CVN impact toughness is observed because of the increase in the Mn content in the weld metal, depending on the weld electrode that was used. This improvement in the CVN impact toughness is 60 % with an increase from 80 to 128 J. The toughness of the WM increases with the increasing Mn content of the weld electrode used. With the use of an S3MoTiB weld electrode instead of an S2Mo electrode as the first electrode at the inner and outer weld seam, which contains Ti (0.15 wt.%) and B (0.013 wt.%) for weld sample D, the measured CVN impact toughness increases from 80 to 144 J at −20 °C with an increase in the Ti content in the weld metal of type I-X65 from 0.0028 to 0.0265 wt.% for weld samples A and D, respectively. The obtained improvement in the CVN impact toughness is 80 %. The highest toughness corresponds to the weld metals of weld sample D for type I-X65 steel and can be attributed to their higher content of Ti, which is known to improve the steel toughness. O and N are known to be harmful elements that reduce toughness. Ti bonds with O and N in the form of TiN and TiO to indirectly improve toughness. In addition to Ti, an S3MoTiB weld electrode consists of a high amount of Si (0.29 wt.%) and B (0.013 wt.%), but the amount of B in the weld metal is not determined. Table 10 shows the CVN impact toughness values of weld sample A at −60, −40, −20, 0 and 20 °C. The transition temperature curve of the type I-X65 weld metal is showed in Fig. 4. While the changes in BM and HAZ toughness are limited at different temperatures, WM toughness changes dramatically.

The weld bead shape, which affects the mechanical properties of the HAZ and WM, is a crucial factor in determining the quality of welds. The macrostructures of the welded joint,

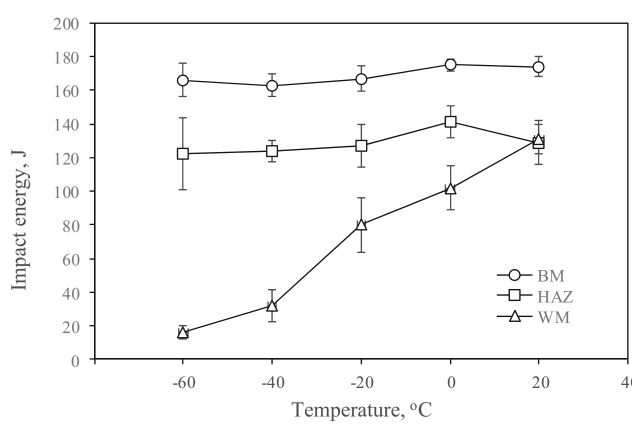

Fig. 4 The CVN impact toughness of sample A conducted at −60, −40, −20, 0 and 20 °C

including WM, HAZ and BM have been examined by optical microscopy at each welding condition. The penetration and reinforcement areas are proportional to heat input. Because the welding parameters such as current, voltage, welding speed and heat input are the same for all applications; the weld bead geometry is similar. The maximum and minimum values of weld bead widths, reinforcement heights and penetrations are given in Table 11 for type I-X65 and type II-X65 steels and there are no significant changes.

4 Conclusion

The effect of weld electrode and base metal composition on the mechanical properties and toughness of weld metals in API-X65 line-pipe steel produced by the SAW technique has been investigated and the following conclusions have been obtained.

The yield strength, tensile strength, elongation % and the CVN impact toughness of the base metal and weld metal welded at the same conditions are changed by using type II-X65 instead of type I-X65.

Since the applied welding parameters and used flux are the same for all type I-X65 applications, the differences in the chemical composition of the weld metal mainly depend on the weld electrode that was used.

While the ultimate tensile strengths of WM are higher than BM, the elongation and area reduction percentages are lower than BM for all applications. The tensile strength, elongation and area reduction percentages of WM are changed by using different weld electrodes. A slight increase in WM hardness is observed.

The CVN impact toughness of the WM is improved by increasing Mn content of the weld electrode used. The existence of Ti in the weld electrode improves the CVN toughness and ductility with a slight loss of tensile strength of WM with an increase of Ti content. The toughness of WM is lower than that of BM and HAZ for all applications.

The usage determination of a proper weld electrode composition has high importance in obtaining a suitable microstructure that is proven to develop the properties of welds and to increase the mechanical properties of welds for low-carbon steels.

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