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Investigation of the Effect of Solid Wire and Flux Combinations Used in Submerged Arc Welding of the LPG Cylinders on Mechanical Properties

Uğur NUHOĞLU[*1] ORCID *0000-0003-2807-4848*
Tolga MERT[2] ORCID *0000-0003-2407-3426*
Mustafa TÜMER[3] ORCID *0000-0002-1931-4750*

[1]Yıldız Technical University, Graduate School of Science and Engineering, Istanbul
[2]Yıldız Technical University, Mechanical Engineering Department, Istanbul
[3]Kocaeli University, Welding Technology Program, Kocaeli

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Abstract

Liquefied petroleum gas (LPG) cylinder is a type of pressure vessel that used to store and transport liquefied gases. In this study, S460MC steel with a thickness of 1.50 mm and submerged arc welding method were used in the manufacturing of LPG cylinders. Selection of the welding consumables (wire, flux) and optimization of the welding parameters (current, voltage, travel speed) are the primary focus of the study. Selected welding parameters have been verified as a result of visual and radiographic (X-ray) tests and macroscopic examinations. In order to analyze the effects of welding consumables on mechanical properties, test specimens were prepared, then tensile and hardness tests were performed and it was observed that molybdenum element increased the mechanical strength. In order to fulfill the requirements of the LPG cylinder production standard, bursting & volumetric expansion tests and pressure fatigue tests were performed and the requirements were met.

Keywords: LPG cylinder, Submerged arc welding, HSLA steel, Molybdenum, Mechanical strength

LPG Tüplerinin Tozaltı Ark Kaynağında Kullanılan Kaynak Teli ve Kaynak Tozu Kombinasyonlarının Mekanik Özelliklere Etkisinin İncelenmesi

Öz

Sıvılaştırılmış petrol gazı (LPG) tüpü, sıvılaştırılmış gazları depolamak ve taşımak için kullanılan bir tür basınçlı kaptır. Bu çalışmada, LPG tüpü imalatında kalınlığı 1.50 mm olan S460MC çeliği ve tozaltı ark kaynağı yöntemi kullanılmıştır. Kaynak sarf malzemelerinin (tel, toz) seçimi ve kaynak parametrelerinin

[*]Sorumlu yazar (Corresponding author): Uğur NUHOĞLU, *ugurnuhoglu1461@gmail.com*

(akım, gerilim, ilerleme hızı) optimizasyonu çalışmanın öncelikli odak noktalarıdır. Görsel ve radyografik (X-ışını) testler ve makroskopik incelemeler sonucunda seçilen kaynak parametreleri doğrulanmıştır. Kaynak sarf malzemelerinin mekanik özellikler üzerine etkilerini incelemek amacıyla deney numuneleri hazırlanmış sonrasında çekme ve sertlik ölçme testleri yapılmıştır ve molibden elementinin mekanik dayanımı arttırdığı gözlemlenmiştir. LPG tüp üretim standardı gereksinimlerini doğrulamak amacıyla da patlatma & hacimsel genleşme deneyleri ve basınçla yorulma deneyleri uygulanmıştır ve gereksinimler sağlanmıştır.

Anahtar Kelimeler: LPG tüpü, Tozaltı ark kaynağı, Yüksek mukavemetli düşük alaşımlı çelik, Molibden, Mekanik dayanım

1. INTRODUCTION

LPG cylinder is a product that is open to gains and improvements in terms of material consumption, logistics costs and transport ergonomics. The primary step to achieve these improvements is to reduce the weight of LPG cylinders. In this direction, it is necessary to reduce the thickness of the steel used as a raw material. In order to provide the required mechanical strength after the thinning of the wall thickness, materials with higher mechanical strength values than conventional LPG cylinder steels should be used.

Pressure vessels are equipment that are closed to the atmosphere used in the production, transportation or storage of industrial gases, fuel gases and steam [1]. LPG cylinder is a type of pressure vessel that requires high tensile and compression strength to store pressurized gases. The steel of the pressure vessel should not be affected or weakened by the planned content (LPG) and not cause a dangerous effect. The steel must be resistant to brittle fracture and stress corrosion cracking. The steel cylinders are manufactured either in two piece or three-piece construction. In two-piece construction, cylinders are fabricated by welding two domed ends together. The strength characteristics of the welds in the finished cylinder should meet all the requirements, which are specified in the TS EN 14140 for the design and calculation of the cylinder [2, 3]. S460MC is a high strength low alloy (HSLA) ferritic-pearlitic structural steel with minimum yield strength of 460 MPa. Welding techniques with minimal heat input are recommended to maintain the fine structure providing high strength properties [4]. Submerged arc welding is an arc welding method in which the heat required for welding is generated by the arc formed between the melting electrode and the workpiece. Due to its high productivity, submerged arc welding (SAW) is preferred rather than many welding processes. SAW process offers significant advantages such as high reliability, stable arc, no spatters, no fumes or radiation, deep penetration and excellent surface finish of welds. In submerged arc welding, welding metal is formed by the chemical and physical reaction among filler metal, base metal, and welding flux. While the arc, the weld metal and the base metal are protected by the flux and slag (molten flux). Welding flux also reacts with the weld pool and deoxidizes the weld metal. Welding fluxes used when welding alloy steels may contain alloying elements that balance the chemical composition of the weld metal. Welding flux and welding wire should be chosen precisely to obtain a good compatibility between base and weld metals. The alloying elements in flux can be used to enhance the mechanical properties and crack resistance of the weld bead [5-7]. Welding parameters such as current, voltage and travel speed are the principal parameters of submerged arc welding (SAW). Increasing the welding current to improve deposition rate, leads to an increase in heat input [8, 9]. In addition, this leads to deeper penetration and higher melting rate of welding wire. Lack of penetration or incomplete fusion may occur if the current is too low. Essentially, the arc voltage determines the shape and appearance of the weld bead section. While current and travel (welding) speed are constant, increase in voltage results in a flatter and wider weld bead [10].

Steel is an iron (Fe) - carbon (C) alloy. In addition to carbon, steels are also alloyed with different elements such as Mn, Si, Cr, Ni, Mo, V, W, Al, etc. In terms of weldability, carbon and low alloy steels can be divided into different classes such as carbon steels, high-strength low alloy steel or heat-treatable low alloy steels. HSLA steels are designed to provide better mechanical properties than conventional carbon steels. They are generally classified according to mechanical properties rather than chemical compositions. The weldability of most HSLA steels is similar to that of mild steel. The carbon equivalents (CE) are kept low for good weldability [11].

S460MC steel is a weldable and cold formable material with high mechanical strength. Therefore, it was used as a raw material in the manufacturing of LPG cylinder. The scope of this study is as follows; optimization of submerged arc welding parameters, selection of welding consumables, destructive & non-destructive tests and the evaluation of the effect of welding consumables on mechanical properties.

2. MATERIALS AND METHODS

2.1. Base and Filler Metal

This part can be handled in two parts; the steel material used in the manufacturing of the LPG cylinder and the consumables (welding wire and welding flux) used in circumferential submerged arc welding. S460MC was used as a base material for the manufacturing of the LPG cylinder due to its high strength and its chemical composition for weldability. The mechanical and chemical properties of the S460MC steel are shown in Table 1 and Table 2. Due to their completely adjusted chemical composition and precisely controlled thermo-mechanical processes, their strength and ductility are maintained.

Table 1. Mechanical properties of S460MC [12]

Standard	Quality	Re, (N/mm^2)	Rm, (N/mm^2)
EN 10149-2	S460MC	460 (min.)	520-720

Table 2. Chemical composition of S460MC [12]

Standard	%C max.	%Mn	%P max.	%S max.
	0.12	1.00-1.60	0.025	0.015
EN 10149-2	%S max.	%Si max.	%Al	%Nb max.
	0.015	0.3	0.015-0.060	0.09

In order to obtain good results in welded joints, base metal and filler metal chemical compositions must be compatible [13]. Two different wire-flux combinations were selected to analyze the effect of welding consumables on the circumferential weld of LPG cylinders. By taking into consideration the thickness of the base metal to be welded (1.50 mm), welding wires were selected with 1.60 mm diameter for experiments. The wire-flux combinations used are given in Table 3.

Table 3. Wire-flux combination

Standard	Code	Wire	Flux
EN ISO 14171-A	S1	S 42 A AR S1	S A AR 1
	S2Mo	S 46 3 AB S2Mo	S A AB 1

S1 is a solid, submerged arc welding wire suitable for welding general structural steels with tensile strengths up to 510 N/mm², used in pressure vessel, pipe, shipbuilding and steel constructions [14]. S A AR 1 is a rutile type, agglomerated submerged arc welding flux, which is designed for welding of at high speeds with excellent bead appearance [15]. S2Mo is a Mo-alloyed and solid, submerged arc welding wire suitable for welding general structural steels, low alloyed steels with medium and high tensile strengths, used in pressure vessel, boiler, tanks, pipe and heavy steel constructions [16]. S A AB 1 is an alumina-basic type, agglomerated submerged arc welding flux [17]. The chemical compositions and mechanical properties of welding wires given by supplier are shown in Table 4.

Table 4. Typical mechanical properties and chemical content of S 42 A AR S1 and S 46 3 AB S2Mo welding wires [15,17]

	Elements (%wt.)				
Wires	**C**	**Si**	**Mn**	**Mo**	
S 42 A AR S1	0.07	0.03	0.55	-	
S 46 3 AB S2Mo	0.05	0.30	1.35	0.35	
Mechanical properties	Re (N/mm^2)	Rm (N/mm^2)	Elongation (%)	Charpy V-notch properties (J)	
S 42 A AR S1	460	530	28	20°C → 60	0°C → 30
S 46 3 AB S2Mo	510	570	26	20°C → 100	-40°C → 50

2.2. Welding and Experimental procedure

Lincoln Electric AC/DC 1000® SD welding machine and MAXsa® 10 control unit were used for the circumferential submerged arc welding of the LPG cylinder. In the mechanism where the welding process is carried out, the welding torch can be adjusted to the desired position, then the LPG cylinder is rotated in the horizontal position and welded. The welding set-up is shown in Figure 1. 200 mm trial weld beads were prepared with nine different combinations of current, voltage and travel speed. The parameter combinations of these trial runs are shown in Table 5.

Visual and radiographic inspections and macroscopic examinations were carried out for the prepared weld specimens. During the visual inspection, incomplete fusion was observed in the weld beads of the W-1 and W-2 coded runs.

No visual defects were observed for other weld beads. The incomplete fusion is shown in Figure 2. After the visual inspection, radiographic tests (X-ray) were performed for each welded specimen according to TS EN ISO 17636.

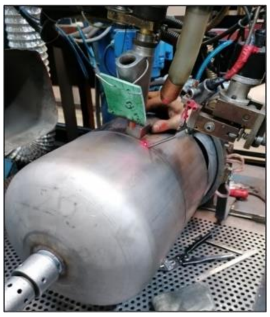

Figure 1. Welding set-up

Table 5. Parameter combinations

Run	Current (A)	Voltage (V)	Travel speed (cm/min.)	Weld length (mm)	Heat Input (kJ/mm)
W-1	240	26	90	200	0.42
W-2	245	26.5	100	200	0.39
W-3	250	27	110	200	0.37
W-4	255	27.5	90	200	0.47
W-5	260	28	100	200	0.44
W-6	265	28.5	110	200	0.41
W-7	270	29	90	200	0.52
W-8	275	29.5	100	200	0.49
W-9	280	30	110	200	0.46

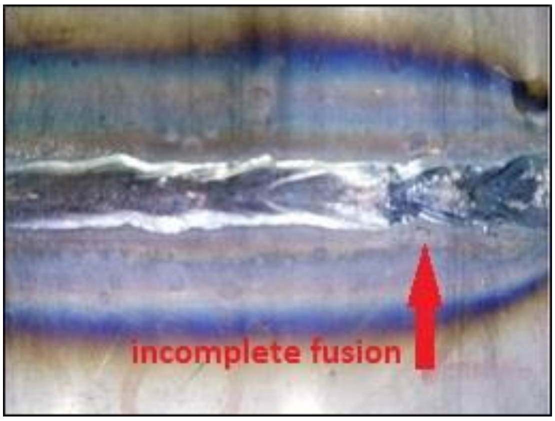

Figure 2. Incomplete fusion

Macroscopic examination was performed in accordance with TS EN ISO 17639. Welded specimens were sanded with 30, 180 and 600 grit sand papers. Then, etching was carried out in accordance with ISO/TR 16060. 5 ml of nitric acid (HNO_3) and 95 ml of ethanol (C_2H_5OH) solution was used as an etchant.

Except the lack of penetration in the specimen welded with W-5 run, no weld defects were observed in the macro image of any specimen. It was evaluated that this defect was not caused by the selection of the welding parameter but caused by the axial misalignment in the weld groove.

The complete penetration in the macro images of other specimens welded with parameters similar to W-5 also supports this inference. However, in the continuation of the study, the welding parameters of W-5 were verified by additional tests. The parameters of W-5 run were chosen as the welding parameters to be used with the S1 and S2Mo coded runs.

Bursting & volumetric expansion and pressure fatigue tests were performed for these specimens in accordance with TS EN 14140 (Figure 3). Since these tests should be performed for the whole body of LPG cylinder, three specimens were welded with same parameters. In order to analyze the effect of consumable selection on mechanical properties, tensile tests per EN ISO 4136 and hardness test per TS EN ISO 9015-2 were carried out [18-19].


Figure 3. a) Bursting & volumetric expansion test set-up, b) Pressure fatigue test set-up

3. RESULTS AND DISCUSSIONS

3.1. Visual Test, Radiographic Test, Macroscopic Test

As in the parameter optimization trial phase, visual and radiographic inspections and macroscopic examination tests were also performed initially. Each specimen has passed these three tests successfully. Thus, the welding parameters of W-5 trial run were verified at this stage. The macro image and radiographic inspection of welded cylinders with S1 and S2Mo consumables (wire&flux) using W-5 parameters are shown in Figure 4.

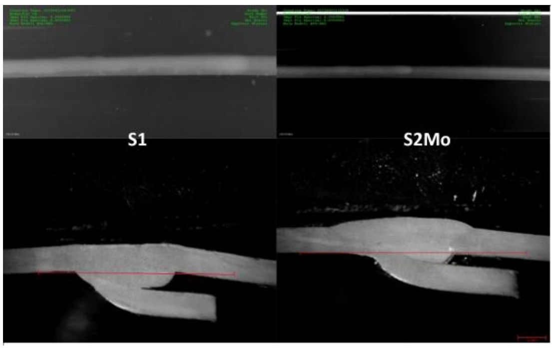

Figure 4. The macro image and radiographic inspection

3.2. Bursting & Volumetric Expansion Test

Bursting & volumetric expansion tests were performed according to TS EN 14140. Accordingly, the cylinder was pressurized until it burst. The difference between initial volume (V_i) and final volume (V_f) of the LPG cylinder was proportioned to the initial volume, thus the volumetric expansion ratio was calculated. Tested cylinders are shown in Figure 5 and the test results are shown in Table 6. As a result of bursting & volumetric expansion tests, the bursting pressure measured for each specimen was above 67.5 bar, which meant that burst pressure requirement was met in accordance with TS EN 14140. Volumetric expansion values were calculated under 17% for each specimen. However, according to TS EN 14140, it is possible to manufacture the cylinders free from the volumetric expansion criteria by equipping them with a pressure relief device (valve with safety valve, etc.).

3.3. Pressure Fatigue Test

Pressure fatigue tests were performed according to TS EN 14140. The cylinders were filled and discharged with water and tested with repetitive hydraulic pressures, where upper pressure is 30 bars and lower pressure is 3 bars. The cycle frequency is 9 cycles/min. Test results are shown in Table 7. As a result of the pressure fatigue tests, all specimens met the criteria by resisting to a minimum of 12.000 cycles in accordance with TS EN 14140. After reaching 12.000 cycles these tests were terminated. The reason why S1 specimen shows higher cycle than S2Mo specimen is that S1 specimen's test was performed overnight and it had far exceeded 12.000 cycles already before the test was stopped.

Figure 5. Cylinders subjected to bursting & volumetric expansion test

Table 6. Bursting & volumetric expansion test results

Specimen code	Vi (Lt)	Vf (Lt)	(Vf-Vi)/(Vi) (%)	Bursting pressure (bar)
S1	26	26.76	2.9	99.62
S2Mo	26.35	27.17	3.1	86.91

Table 7. Pressure fatigue test results

Specimen code	Cycle		Pressure (bar)	
	Number	Frequency (cycles/min.)	Lower	Upper
S1	16620	9	3	30
S2Mo	12200	9	3	30

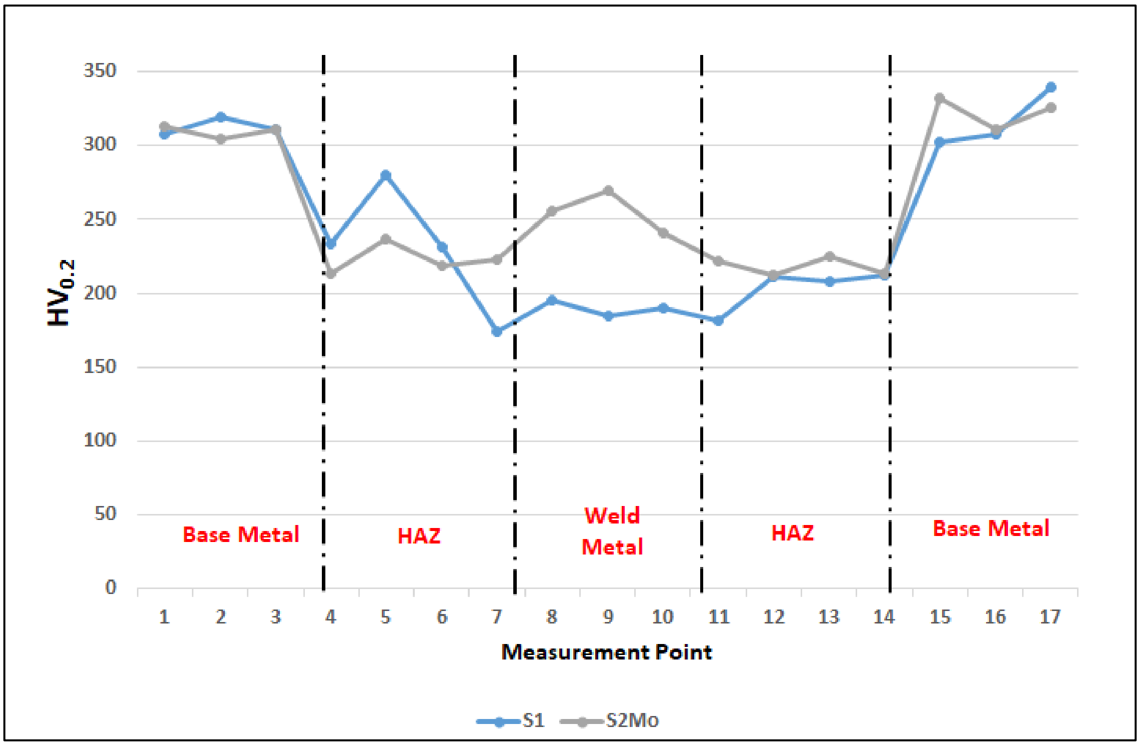

Figure 6. Hardness results

3.4. Hardness Test

Hardness values for two wire-flux combinations are given in Figure 6. Base metal's hardness value is 313±12 $HV_{0.2}$. Significant drops in hardness in HAZs of S1 and S2Mo specimens compared with the base metal take attention. HAZ hardness values for S1 and S2Mo specimens were measured as 229±24 $HV_{0.2}$ and 220±9 $HV_{0.2}$, respectively. Weld metal hardness obtained with S2Mo wire was 31% higher than the one obtained with S1 wire. Weld metal hardness measurements for S1 specimen show close results with its HAZ. Although there is a tendency for hardness decrease in weld metal and HAZs, cylinders welded with two wire-flux combinations fulfill the necessities of standards in bursting & volumetric expansion tests as well as pressure fatigue tests. The increase of Mo content creates grain-refined weld metal microstructure with impressively improved toughness. Significant amounts of Mo (*0.1 wt%) provides excellent properties in weld metals of alloy steels. In addition, the effect of Mo on the microstructure and thus the hardening takes place in conventional steels [20, 21]. In a previous study, besides the effect of Mo, hardness values decreased with increasing heat input. Also, high heat input negatively affected the toughness values [22]. The most important reason why the hardness values of the S2Mo weld metals are partially lower than the base metal is the high heat input provided by the selected welding method. Despite the decreasing of hardness in weld metal and HAZ, the damages occurred in the base metals in the bursting & volumetric expansion and pressure fatigue tests.

3.5. Tensile Test

Transverse tensile tests were performed in accordance with TS EN ISO 4136. As a result of the tensile tests, it was observed that base metals fractured. All of the tensile strength (R_m) values were higher than the minimum tensile strength value of S460MC steel, which is between 520-720 N/mm^2 according to EN 10149-2. The average tensile strength value of S2Mo combination was 744.5 N/mm^2, and the average of S1 combination was 684.5 N/mm^2. S2Mo welding wire contains 0.35% Mo. The main purpose of adding molybdenum into the weld metal is to improve the weld strength [5, 23]. In this direction, the strength improving effect of molybdenum was confirmed by tensile and hardness tests.

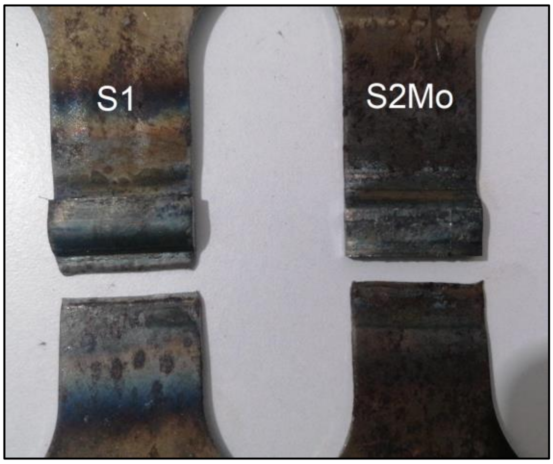

Figure 7. Tensile test specimens. S1 specimen (left), S2Mo specimen (right)

4. CONCLUSIONS

This study examined the effect of different filler metal and flux combinations on mechanical properties of submerged arc welded S460MC steel. According to the results above, the following conclusions can be drawn:

- Both filler metal combinations have successfully completed the bursting & volumetric expansion and pressure fatigue tests in line with the requirements of the relevant standards.
- Due to the Mo content of S 46 3 AB S2Mo wire, hardness and tensile strength values were higher than the LPG cylinder welded with S 42 A AR S1 wire. Since Molybdenum is a strong carbide forming element, carbide segregation at grain boundaries increases hardness. In addition, enhancement in tensile strength is due to solid solution strengthening mechanism [23]. The softening in the HAZ regions is almost similar due to the same heat inputs for either combination.
- If the working conditions are evaluated for strength, S1 denoted filler wire and flux combination (S 42 A AR S1 wire and S A AR 1 flux) can also be used safely.

5. ACKNOWLEDGEMENT

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