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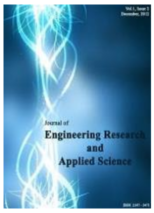

The effect of the gap between the materials on the weld penetration and mechanical values in the MAG butt weld joint

K. Ermis[1,a], E. Celikten[2]

[1]Sakarya University of Applied Sciences, Mechanical Engineering, Sakarya, Turkey.
[2]Sakarya University of Applied Sciences, Graduate Education Institute, Sakarya, Turkey.

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Abstract
The welding sector, which is developing and progressing rapidly, is one of the methods of combining the same or different material groups. The welding procedure should be capable of producing weldments with adequate strength, ductility, and toughness to satisfy the applicable specifications. Although the welding parameter values are adjusted according to the welding method verification reports, variations in the distance between the materials to be joined may occur due to reasons such as non-rigid or deformed fixtures, operator loading errors during application. These errors together with insufficient weld penetration error give variable shrinkage values in mechanical test results. In this study, S460M thermo-mechanically rolled fine-grained steel plate materials with the same thickness and same parameter values as robotic MAG welding were combined with three different joint gap distances (0 mm, 1 mm, and 2 mm) under shielding gas combinations using MAG welding method. The effect of the gap distance left at the joints of two plates before welding on the weld penetration depth and mechanical values was examined. As a result of the analysis, the best penetration depth and mechanical properties were obtained in the joint where the joint gap distance between the two welded parts was 2 mm.

Keywords: MAG, butt weld joining, depth of penetration, mechanical properties.

1. Introduction

The welding method is a joining method that is frequently used in the manufacture of structural metal parts and related assemblies [1]. When considered in terms of mechanical design, the mechanical and properties of the base material should generally be considered in the design of a component. The most critical mechanical effects of welding are cracking, distortion, and buckling [2]. However, in critical applications, such as defense and aerospace or automotive subcomponents requiring impact resistance, if there is a welded joint, the mechanical properties of the weld metal and the heat-affected zone (HAZ) and impact/collision their behavior under downloads should be taken into account. The reason for this is that the HAZ region near the welded joint in thermo-mechanical rolled steels, which gives strength with grain refinement, is more sensitive than the main material in terms of mechanical properties. As HAZ is the region subject to grain growth, it generally represents the weakest link of the welded assembly. For this reason, mechanical behavior characterization is important, especially in terms of events that create high strain rates such as collision or explosion effects and in regions with a heterogeneous internal structure such as the HAZ region.

For high strength steels, some researches have been reported on high-temperature mechanical properties of several grades, S460 [3–7]. The strength of welded was investigated in S460 steel columns at elevated temperatures [8] using finite element analysis [9]. Experimental and numerical analyzes of butt-welded S460 joints were investigated by Wudtke et all. [10].

Due to the rapid cooling, the internal structure of thermomechanically rolled steel is finer than structural steel. For this reason, its mechanical values are much superior to structural steels. Depending on their carbon content, thermo-mechanical rolled steels; It is divided into 3 groups as thermo-mechanical rolled steels with reduced perlite, low perlite and non-perlite. This fine grain steel group has higher weldability than normalized steels due to their low carbon content and does not require preheating.

In this study; the S460M (ISO 10025-3) sample, one

[a] Corresponding author; ermis@subu.edu.tr

of the fine-grained material group types that do not require preheating, was selected. Three different gap distances are left on the welded joint of this selected sample (0 mm, 1 mm, and 2 mm). The effect of distances on weld penetration depth and mechanical values has been investigated.

2. Mathematical and method

Nowadays, fine-grained structural steels are used in the automotive industry, in the construction of resistant boats of surface and submarine ships, in the machinery industry, in power generation facilities, in pipelines, in crane and pipe construction, and many other sectors. When welding high-strength steels, the weld metal should penetrate smoothly with the base metal at the weld joint root and on the joint surfaces in full penetration butt welding or corner welding type welding applications. Excessive weld filler should be avoided [11]. Heat treatable fine-grained steels (HTLA: heat treatable low alloy) have high hardening properties and are very sensitive to hydrogen cracks in the weld metal and the heat-affected zone (HAZ). In order to prevent hydrogen cracks, the arc welding method is applied with low hydrogen content welding electrodes and powders by applying sufficient preheating and transition temperatures [12]. The mechanical properties of the welding wire used in this study are shown in Table 1. Carbon and manganese are the two most important elements that affect the hardening ability of unalloyed steel.

Table1. SG3 welding wire mechanical properties

Mechanical properties - typical	
Yield strength, N/mm²	470 N/mm²
Tensile strength, N/mm²	570 N/mm²
Elongation (L=5d)	25 %
Notch impact strength	60 J (-30°C)

In low alloy steels, in addition to the carbon and manganese in the composition of the steel, alloying elements such as chromium, molybdenum, vanadium, nickel, and copper also contribute to hardness. In order to determine the contribution of these elements to hardness, the concept of carbon equivalent was created. In the expression of carbon equivalent, the amount of carbon that gives the hardness equivalent to the hardness formed by the alloying elements in the composition of the steel is called Carbon Equivalent [13]. The carbon equivalent formula created by the International Institute of Welding is shown in Equation 1 [14,15].

$$Ceş = \%C + \frac{\%Mn}{6} + \frac{\%Cr+\%Mo+\%V)}{5} + \frac{\%Ni+\%Cu}{15} \quad (1)$$

For S460M thermomechanical rolled steel used in the experimental study, it was calculated as Ceş = 0.30% by using the formula in Equation1. Welding mouth is related to the thickness of the part and the way of joining. It is recommended to open a welding groove to obtain full penetration in the combination of 5 mm and above thick materials where the welding seam will be pulled on both sides. This study aims to obtain full penetration by leaving a gap between 8 mm thick samples without opening the welding mouth and also to prevent the hardness value in the HAZ region from exceeding 350HV.

Within the scope of this study, 8 mm-thick S460M material was joined by the Robotic MAG welding method in 3 different ways. The gap between the materials is set to be 0 mm, 1 mm, and 2 mm. Welding parameters were kept constant in all three test methods. (270 amps, 27 Volts, 5.73 mm/sec wire feed speed). SG3 welding wire ArCo 18% mixed gas was used in the joining method. Chemical composition values of the material used in experimental studies are presented in Table 2.

The mechanical properties of the S460M material obtained from the tensile test results are shown in Table 3.

All trial samples were welded according to the parameter values in Table 4.

Standard dimensions given for hot-rolled, weldable, fine-grained S460M steel according to European Standard, EN ISO 10113, are given in Table 5 [16].

Table 2. S460M chemical composition (wt%)

Chemical composition (wt%)									
C	Mn	Cr	Mo	V	Ni	Cu	Cr	Si	P
0.062	1.400	0.019	0.004	0.004	0.020	0.019	0.019	0.026	0.013
0.059	1.420	0.023	0.004	0.004	0.019	0.016	0.023	0.005	0.014
0.058	1.400	0.021	0.006	0.004	0.030	0.016	0.021	0.004	0.014
0.060	1.393	0.019	0.003	0.004	0.019	0.014	0.019	0.002	0.010

Table 3. S460M tensile properties

Tensile test results				
Temperature (^{0}C)	Yield strength, $R_{p0.2}$ (MPa)	Tensile strength, R_m (MPa)	Elongation at fracture, A (%)	Ratio R_p/ R_m (%)
20	537	614	21.5	87
	550	625	23.5	88
	557	632	22.5	88
	558	623	24.0	90

Table 4. S460M tensile properties

Run 1-2		
Process		135
Filler metal	Class	SG3
	Diameter, mm	1
Current	Polarity	DCEP
	Ampere	270
Volts		27
Wire feed speed, mm/sn		6-8
Travel speed, mm/sn		5.73
Heat input, kJ/mm		1.02

Table 5. Hot rolled, weldable, fine grain steels according to EN 10113 S460M steel standard values.

Thermo-mechanical rolled fine-grain S460M steel			
Tensile strength, N/mm^2	Thickness, mm	≤100	530
Yield strength, N/mm^2		≤16	460
		>16 ≤40	440
		>40 ≤63	430
		>63 ≤80	410
		>80 ≤100	400
Elongation at fracture A% minimum		17	

When Table 3 and Table 5 are compared, it is seen that the S460M steel to be tested conforms to the European Standard. The size information of the samples prepared for fine-grained high-strength steel joined without opening the welding mouth is shown in Figure 1

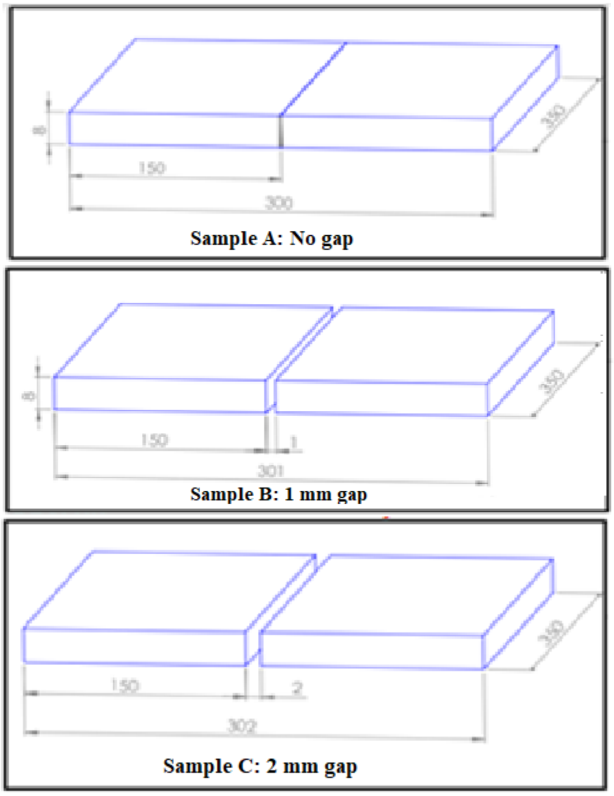

Figure 1. S460M welding samples dimensions.

3. Result and discussion

3.1. Macro-structure ımage analysis results

The macro-structure examinations of the samples obtained were made according to the requirements of EN ISO 17639 standard [17] and the visuals obtained are shown in Figure 2.

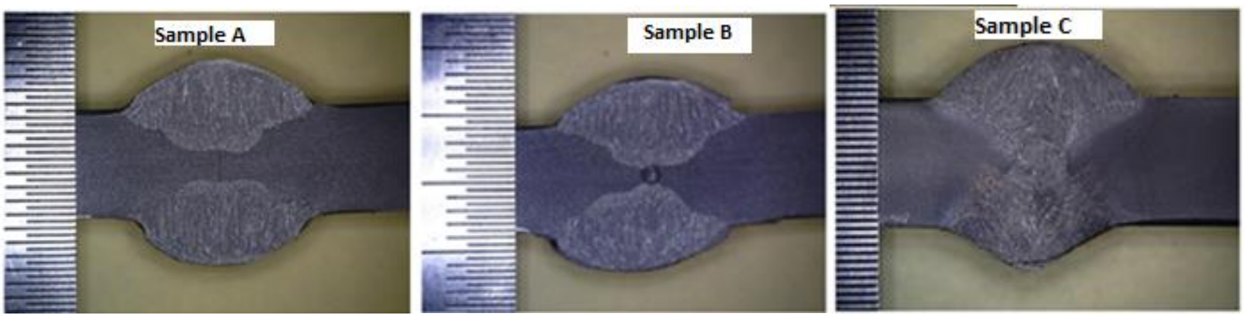

Figure 2. Macro-structure images.

As a result of the macro-structure images, no tear, crack, etc. welding error was found, but Sample A and Sample B, as per the TS EN ISO 5817 standard error code numbered 402, "There is a lack of penetration error, and for welded samples evaluated according to the C quality level, this error is not detected according to the standard. It is said, "not permissible". Sample 3 has full penetration and is within the evaluation criteria [18].

3.2. Tensile test results

The tensile test is applied to determine the relationship between the strength of the welded joint and the strength of the base material used. As a result of the tensile test, the maximum load, yield strength, tensile strength, and percent elongation properties of the sample can be determined. As a result of the tensile test, it is expected that the welded sample properties will be equal to the main material properties in terms of the suitability of the method [19].

Tensile samples were prepared according to TS EN ISO 4136 and the values obtained are given in Table 6. When the results are examined, the rupture on the base material in all three samples shows that the tensile strength of the weld zone and the HAZ region is higher than the base material. However, the Rm value for S460M thermomechanically rolled fine grain steel is stated as 614 MPa.

The tensile value of the sample subjected to the tensile test is expected to be higher than the tensile value of the main material [20].

Table 6. Tensile-elongation results of the samples

	Sample A	Sample B	Sample C
Cross section area, mm^2	202.438	203.076	204.144
Starting length, L_0, mm	75	75	80
Elongation length, L_0, mm	89.94	89.86	92.53
Yield strength, R_p %0.2, N/mm^2, (MPa)	486	472.4	580.4
Fracture location	Weld	Weld	Materials
Max. force, F_{max}, kN	119.591	122.138	126.804
Tensile strength, R_m, N/mm^2 (MPa)	590.8	601.4	621.1
Elongation, %	19.9	19.8	15.7

3.3. Hardness test results

The hardness test is used to observe the hardness change after welding the welded materials. Hardening in the Heat Affected Zone, where phase transformation and grain coarsening are observed after welding, is of great importance. Although the maximum acceptable hardness values vary depending on the material group, hardnesses above 480 HV are not accepted in any group [19]. According to the EN ISO 15614-1 [21] evaluation standard of thermomechanical steels, it is shown in Table 7.

Table 7. Maximum allowable hardness value (HV 10)

Steel groups ISO 15608	Non-heat treated	Heat-treated
1^a ,2^b	380	320
3^b	450	380
4, 5	380^c	350^c
6	-	350
9.1	350	300
9.2	450	350
9.3	450	350

[a] If hardness tests are required
[b] For steel with min R_{eH} >890 MPA, special values shall be specified
[c] For certain materials, higher values may be accepted, if specified before the welding procedure test

The thermomechanical rolled material group, the heat-not affected zone can be at 380 HV and the heat-affected zone can have a 320 HV maximum hardness value as shown in Table 7. Hardness measurements were taken from the regions shown in Figure 3 to learn the effects of the parameters of sample C and the effects of heat input on the hardness of the material with the result of obtaining a full penetration weld.

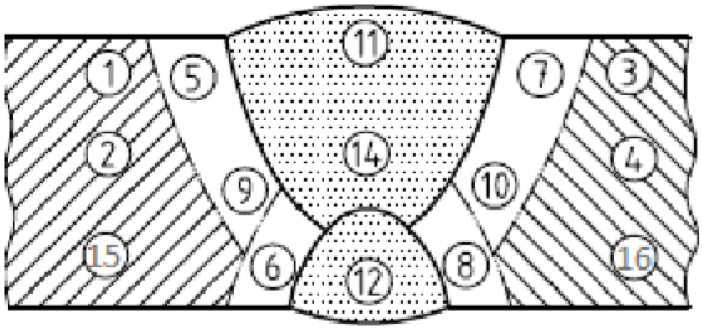

Figure 3.Hardness test measurement points

The hardness measurement results taken from the regions shown in Figure 3 are given in Table 8. In the hardness measurement test results, it has been determined that the hardness value increases as you move from the main material to the weld metal. The reason for the high hardness value of the HAZ zone compared to the main material is that the grain coarsening and cooling rate is high due to the high heat affecting the material during welding.

Table 8. Hardness test measurement results

		Zone	**Track position**	**Hardness value**		
Main material	**Unaffected region**	1	Base metal 1-Surface-Top	219.75	218.24	221.27
		2	Base metal 1-Center	219.5	222.03	222.80
		3	Base metal 2-Surface-Top	225.92	227.51	226.71
		4	Base metal 2-Center	228.31	229.11	227.51
		15	Base metal 1-Surface-Bottom	-	-	-
		16	Base metal 2-Surface-Bottom	-	-	-
	HAZ	5	Base metal 1-ITAB-Top	216.75	227.51	235.69
		6	Base metal 1-ITAB-Bottom	215.28	227.51	238.23
		7	Base metal 2-ITAB-Top	254.38	234.02	222.80
		8	Base metal 2-ITAB-Bottom	253.44	230.73	222.03
		9	Base metal 1-ITAB-Root	218.24	230.73	239.09
		10	Base metal 2-ITAB-Root	251.58	232.37	222.03
Weld metal		11	Weld region-End pass- Top	238.23	239.09	237.38
		12	Weld region-End pass-Bottom	259.16	255.33	257.23
		13	Weld region-Root pass	-	-	-
		14	Weld region-Root pass-Inner	261.21	257.23	261.11

3.4. Notch Impact Test Results

A notch impact test is performed to define the resistance of the material against dynamic forces at certain temperature values of the materials. The notch is placed in the test specimen of the size determined according to the EN ISO 15614-1 standard, in the opposite direction of the impact to be exposed. The hammer dropped from a certain angle and a certain height is made to hit the test sample. The hammer hitting the specimen reaches a certain height. The potential energy calculated between two heights defines the impact energy of the material at the applied test temperature [21].

In order to examine the effect of notch impact strength on the material, in the test conducted according to the requirement of EN ISO 15614-1, 6 pieces of samples measuring 7.5 x 10 x 50 mm were broken at -40 °C. As can be seen in Table 9, as a result of the test studies, it has been determined that while the main material shows the highest notch impact energy, the source region shows the lowest notch impact energy [21].

Table 9. Notch impact test results

Test piece no	Notch location	Notch type	Test Temperature (^{0}C)	Results(J)	
				Test	Average
1	Weld	V	-40	90.58	104.49
2	Weld	V	-40	82.68	
3	Weld	V	-40	140.21	
4	Main material	V	-40	133.74	118.27
5	Main material	V	-40	113.71	
6	Main material	V	-40	107.36	

3.4. Bend test results

The bend test is used in butt welds to determine the ductility and discontinuities between the weld/base material. Bending tests are applied as cap bending, root bending, and side bending. While the cap side of the weld remains under tension in cap bending, the root side of the weld remains under tension in root bending. It is applied in welded joints of materials with a side bending thickness of more than 12 mm and the weld section remains under tension. In this way, any discontinuity (lack of melting, pores, cracks, etc.) is revealed [19]. The test result values of 4 welded samples prepared in 8x20 mm dimensions according to EN ISO 5173 standard [22] are given in Table 10. As a result of the bending test performed up to 180 ° C, no cracks, tears, etc. errors were found in any of the welded samples during the visual inspection.

Table 10. Bending test results

Test piece no	Distance of between rollers (mm)	Diameter of mandrel (mm)	Bending angle	Declaration of conformity
1	52	32	180^0	Suitable
2	52	32	180^0	Suitable
3	52	32	180^0	Suitable
4	52	32	180^0	Suitable

4. Conclusions and discussion

In this study, S460M thermomechanically rolled fine-grained steel sheet materials were joined by the MAG welding method under shielding gas combinations with three different bonding gap distances. After examining the penetration depths of welded joints, tensile, bending, notch impact, and hardness tests were applied to determine the strength of the sample at which full penetration was obtained. As a result of this study, the penetration depths and mechanical effect of the fine-grained thermomechanically rolled materials combined with the MAG welding method under mixing gas were investigated; The following conclusions can be drawn:

- It has been determined that the gap distance between the materials and full penetration at suitable parameter values in field conditions that are not suitable for the application of the proposed welding groove design methods to achieve full penetration in the combination of 5mm and above thick materials.
- The compatibility of the obtained data was determined by comparing the mechanical values of the sample with full penetration according to the welding standards.
- In the tensile test results, a rupture occurred in the base material. These results show that the weld seams are safe.
- When the hardness test result is examined, it was observed that the hardness decrease towards the base material.
- When the notch impact test result is examined, it is determined that the main material shows the highest notch impact energy at -40 ° C.
- As a result of the bending test, cracks, tears, etc. No resource errors were encountered.

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