Influence of Filler Metals on Microstructure and Mechanical Properties of Gas Metal Arc Welded High Strength Steel

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Abstract. Nowadays, the automotive industry shows an ever-growing need for the application of high strength materials. The high strength steels are one of the most important materials used at present; these steels have excellent properties such as high yield strength and low weight. These properties are insured by their versatile and complex microstructures. The use of these steels is advantageous from the standpoint of economic application and fuel consumption. Furthermore, the weight loss of vehicles results in the reduction of pollutants and greenhouse gases emissions. Besides that, the application of high strength steels also causes an improvement in strength, stiffness, and other performance characteristic. In spite of the aforementioned advantages, there are still difficulties with their wider use due to their limited formability and weldability. The welding of high strength steels can be a great challenge because of cold cracking sensitivity, reduction of strength and toughness of heat affected zone and filler metal selection. To take advantage of the outstanding mechanical properties of high strength steels, it is very important to select the appropriate welding method with the exact welding parameters.

In the present research work the effect of the filler metals on microstructure and mechanical properties of a high strength structural steel (Alform 1100M x-treme) having 15 mm thickness welded by gas metal arc welding was investigated. The chosen filler metals were the Böhler Union X96 (undermatching condition) and Böhler alform 1100 L-MC (matching condition). During the welding experiments, the $t_{8/5}$ cooling time was regulated. Based on our former investigations (physical simulations on the examined material) and recommendations in the literature, the chosen $t_{8/5}$ cooling time was 5 s. The welding parameters were determined based on the cooling time. After welding, different destructive and non-destructive investigations (optical microscope, hardness tests) were performed to compare the microstructure and mechanical properties of the joints made by different filler metals.

Keywords: High strength steel · Gas metal arc welding · Mechanical properties

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1 Introduction

Nowadays, the application ratio of high strength steel is continuously increasing. High strength steels have a more and more important role in engineering applications especially in the vehicle and transportation industry. With the increase in fuel consumption and CO_2 and other greenhouse gas emission, environmental safety is becoming a social problem [1]. Thus, the automotive industry is under constant pressure because they need to face with the challenges of strict requirements for lower CO_2 emission, need to improve fuel efficiency by reducing the weight of vehicles and there is customer demand for lower operational costs [2–10]. For the above-mentioned problems, the application of high strength materials, especially high strength steel may a possible solution because the use of these steels leads to building structures and components which are thinner, lighter, yet stronger. Besides, high strength steel may reduce the carbon footprint associated with its manufacturing by lowering the global steel's net production volume and the carbon emission due to the transportation of such heavy materials. Cost-effectiveness for end users is also another benefit which could be gained by weight saving in the structure. The possibly thinner cross-section is a further advantage of high strength steels since they are material-saving and make possible the reduction of production time. Besides decreasing operational and production costs due to the energy-saving in mobile structures, in case of welding thinner plates and smaller cross-sections results savings in the amount of base materials and filler metals applied [3, 11–14].

Despite the good mechanical properties and potential benefits of high strength steels, there are still challenges in the case of their welding. The determination of the right welding technology, including the optimal process window, may still cause difficulties for welding engineers. Welding heat input and cooling rate are the key parameters affecting the joint's capacity, ductility, and toughness. Due to the differences in the cooling rates at the vicinity of the joint, the local heating creates a range of materials with different characteristics depending on their distance from the weld fusion zone. Among these regions, the softening at the heat-affected zone (HAZ) is the most crucial. Due to the thermal cycles experiences during welding, these HAZs can exhibit significant losses in toughness. The degradation of material properties (such as toughness) in the weld HAZ, is required to remain tolerable. Besides that, the filler material selection (in other words, the matching) can also be a problem in case of higher yield strength, but the yield strength of commercial filler metals have already exceeded 1000 MPa [2, 3, 11, 15–19].

2 Materials and Methods

In the present study Alform 1100M x-treme high strength steel plates produced by Voestalpine were used. Based on the material certificate, the mechanical properties – hardness (HV10), yield strength, tensile strength, elongation, and impact energy - and chemical composition are shown in Table 1 and Table 2, respectively.

Table 1. Mechanical properties of the investigated base material.

Thickness [mm]	HV10	Rp0.2 [MPa]	Rm [MPsa]	A [%]	CVN (at −40 °C) [J]
15	394	1193	1221	11, 6	88

Table 2. Chemical composition of the investigated base material [weight%].

C	Si	Mn	P	S	Cr	Cu
0.13	0.32	1.62	0.009	0.0015	0.63	0.047
Ni	Mo	V	Ti	Al	Nb	B
0.32	0.62	0.066	0.011	0.035	0.037	0.0014

The carbon equivalent value indicated in the certificate is CEV = 0.68%.

The microstructure of the examined base material in the delivery state by Zeiss Observer D1 m optical microscope is shown in Fig. 1 (magnification = 200×), where it can be observed the characteristic fine-grained microstructure of the thermomechanically rolled steels. The specimen was etched by Nital (3% HNO_3).

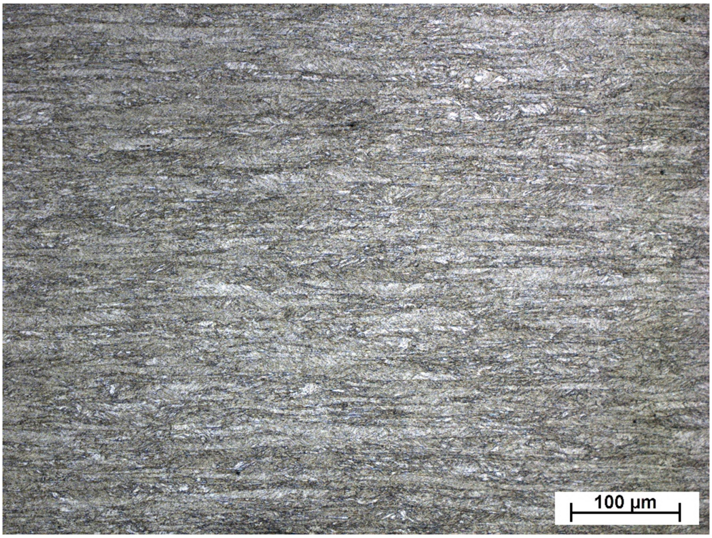

Fig. 1. Microstructure of the base metal in as-received condition, Nital etch

For the welding experiments Böhler Union X96 (Ø 1.2 mm) and Böhler alform 1100 L-MC (Ø 1 mm) filler metals were used. Table 3 and Table 4 contain the chemical composition of the filler metals, and Table 5 and Table 6 contain the mechanical properties of the filler metals based on the material certificates.

Table 3. Chemical composition of the Böhler Union X96 filler metal [weight%].

C	Si	Mn	P	S	Cr	Mo
0.1	0.81	1.94	0.015	0.011	0.52	0.53
Ni	V	Cu	Ti	Al	Zr	
2.28	< 0.01	0.06	0.06	< 0.01	< 0.01	

Table 4. Chemical composition of the Böhler alform 1100 L-MC filler metal [weight].

C	Si	Mn	P	S	Cr	Mo	Ni	V
0.08	0.46	1.54	0.01	0.007	0.64	0.52	2.73	0.22

Table 5. Mechanical properties of the Böhler Union X96 filler metal.

R_{eL} or $R_{p0.2}$ [MPa]	Rm [MPa]	A [%]	CVN (at −50 °C) [J]
≥ 930	≥ 980	≥ 14	≥ 47

Table 6. Mechanical properties of the Böhler alform 1100 L-MC filler metal.

R_{eL} or $R_{p0.2}$ [MPa]	Rm [MPa]	A [%]	CVN (at −40 °C) [J]
$\geq$1100	$\geq$1140–1250	$\geq$10	≥ 27

The welding parameters were determined based on the cooling time. The temperature range between 800 and 500 °C, $t_{8/5}$ is important for identifying potential problems related to unfavourable mechanical properties caused by cooling. To determine the optimal $t_{8/5}$ cooling time heat affected zone tests were performed with a Gleeble 3500 physical simulator in the Institute of Materials Science and Technology at the University of Miskolc. In order to simulate HAZ areas with the lowest toughness, the chosen parts of the HAZ were the coarse-grained (CG), the intercritical (IC) and the intercritically reheated coarse-grained zones (ICCG). To be able to simulate gas metal arc welding (GMAW) processes with low, medium, and high heat input, three different $t_{8/5}$ cooling time, 5 s, 15 s and 30 s were set during the tests. After the simulations, optical microscope and hardness tests were performed. Based on the results (Fig. 2), increasing of the cooling time had a negative effect on the hardness of the steel. In case of higher cooling time even the hardness of the coarse-grained zone did not reach the hardness of the base material, the investigated high strength steel was softened on account of the welding heat cycles. Thus, as the result of physical simulations on the examined material and recommendations in the literature, the chosen $t_{8/5}$ cooling time was 5 s. The welding parameters that were calculated based on the cooling time are shown in Table 7, respectively.

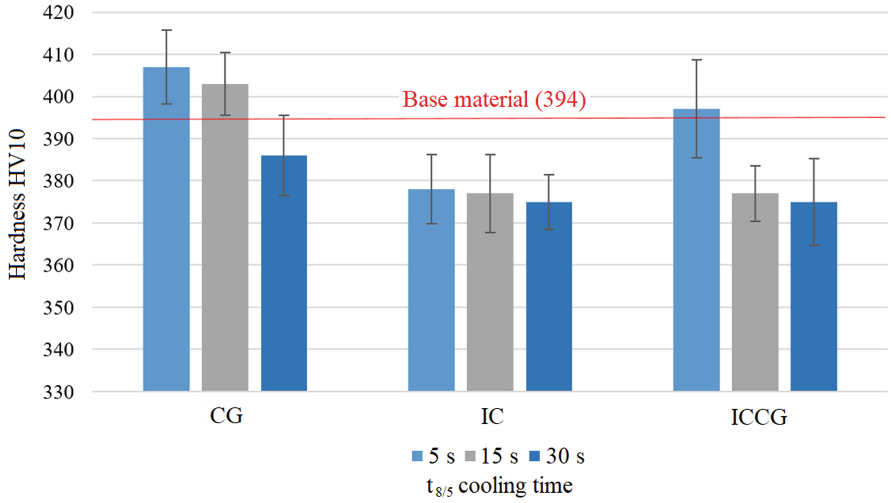

Fig. 2. Result of the hardness tests.

Table 7. Welding parameters.

Filler metal	Welding pass number	Welding current [A]	Welding voltage [V]	Welding speed [cm/min]	t8/5 cooling time [s]	Heat input [J/mm]
Böhler Union X96	1	180	19.1	24	5	688
	2	190	19.7	27		666
	3–4	260	25.1	50		624
	5–8	280	28,7	61		632
Böhler alform 1100 L-MC	1	180	19.1	24		688
	2	190	19.7	27		666
	3–4	240	22,7	42		623
	5–8	260	25,1	50		624

The plate dimensions were 350 × 150 × 15 mm for GMAW. The welding was performed in PA position using Daihen WB-P500L power source. A schematic illustration

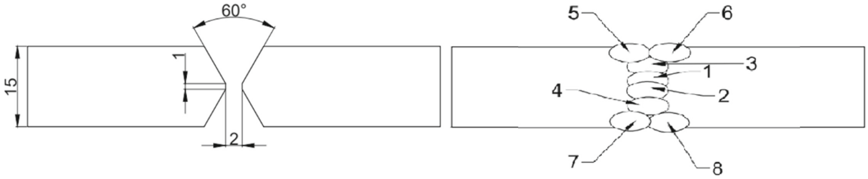

Fig. 3. Schematic illustration of the X-groove and the welding passes.

of the X-groove and the welding passes are shown in Fig. 3. The welding torch was moved by ESAB Miggytrac B5001 welding tractor. The preheating temperature was 100 °C and the interpass temperature during the welding experiments was about 130 °C. A shielding gas mixture of 80% Ar + 20% CO_2 (M21) with a flow rate of 18 l/min was used.

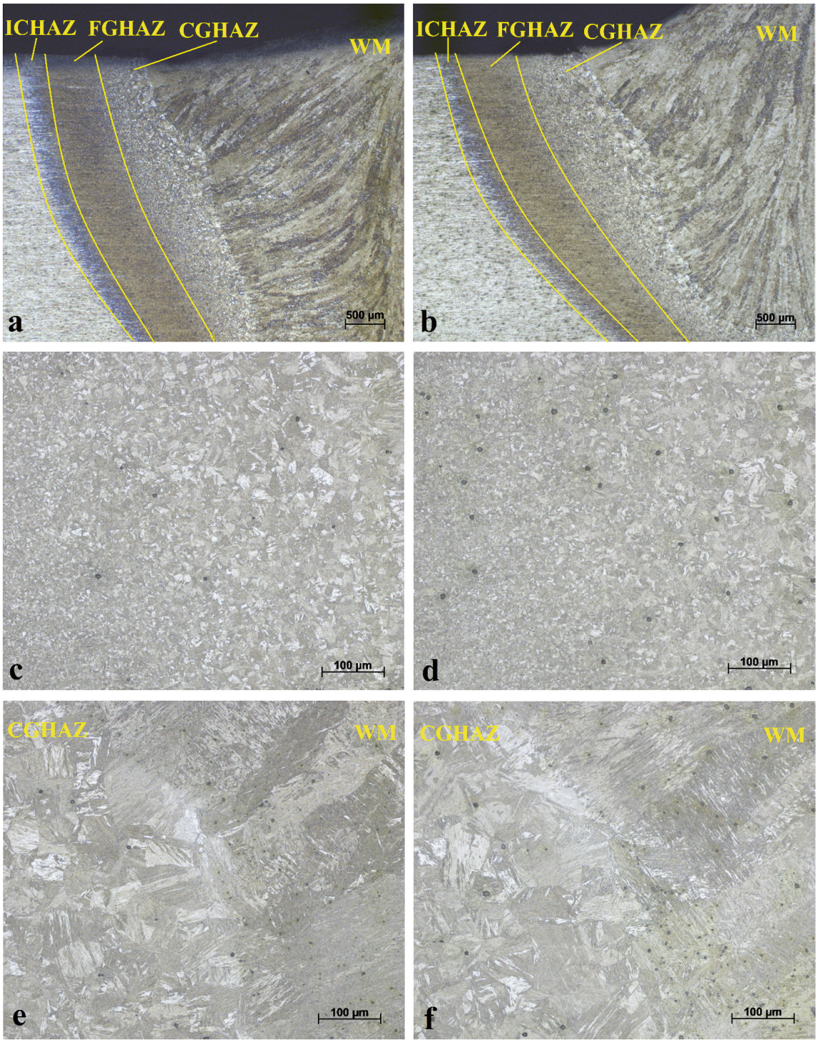

Fig. 4. Optical microscopic images of the welded joints, Nital etch a), c) and e) joint with the use of Böhler Union X96 filler metal; b), d) and f) joint with the use of Böhler alform 1100 L-MC filler metal (ICHAZ = intercritical heat affected zone, FGHAZ = fine grain heat-affected zone, CGHAZ = coarse-grained heat-affected zone, WM = weld metal).

3 Material Tests

Firstly, all welded joints were X-ray tested according to the EN ISO 17636–1:2013 standard [16]. Based on the tests, the most common imperfection was gas porosity. After cutting, all the cross-sections were ground, polished and etched by Nital (3% HNO_3) for optical microscopic investigations. The microstructure of the joints by Zeiss Observer D1 m optical microscope can be seen in Fig. 4.

Based on the optical microscope images, there are no visible differences in the microstructure of the welded joints due to the similar heat input and cooling times applied. In Fig. 3 a) and b) the total width of the different heat-affected zones are also similar. Due to the different composition of the applied filler metals, some difference in the weld metals is visible.

After optical microscopic investigations, Vickers hardness HV10 tests were performed. A Reicherter UH 250 universal macro-hardness tester was used for the measurements. In the case of both weldments, the hardness was measured in three different parts (lines) of the specimens (joints), in every location at three points in the base metal, in the HAZ and in the weld metal. The distribution of hardness points is presented in Fig. 5.

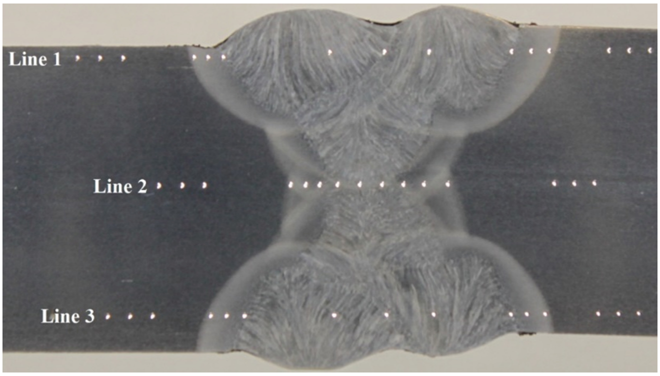

Fig. 5. Hardness points distribution.

The values of hardness in each measured points for the two applied filler metals are presented in Fig. 6 and Fig. 7, respectively.

Thermo-mechanically controlled high strength steels belong to the 2.2 steel group, according to MSZ CEN ISO/TR 15608:2021 [21]. Based on the ISO 15614–1:2017(E) standard in the case of Vickers hardness testing with a load of HV10 the permitted maximum hardness values in the case of non-heat treated steels should be under 380 HV10 [22]. Based on the remark in the standard special values shall be specified for steels with minimum yield strength > 890 MPa. In the case of the examined steel most of the measured hardness values are higher than 380 HV10, even the average value of the base metal would be higher than the given amount in the standard. According to the hardness distribution diagram, the lowest hardness values were in the heat-affected zone of the root in

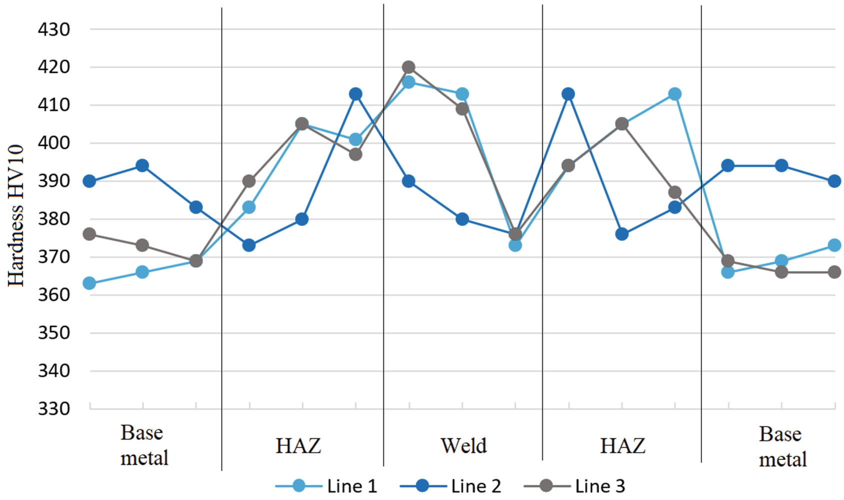

Fig. 6. Hardness distribution for weldments with Böhler Union X96 wire.

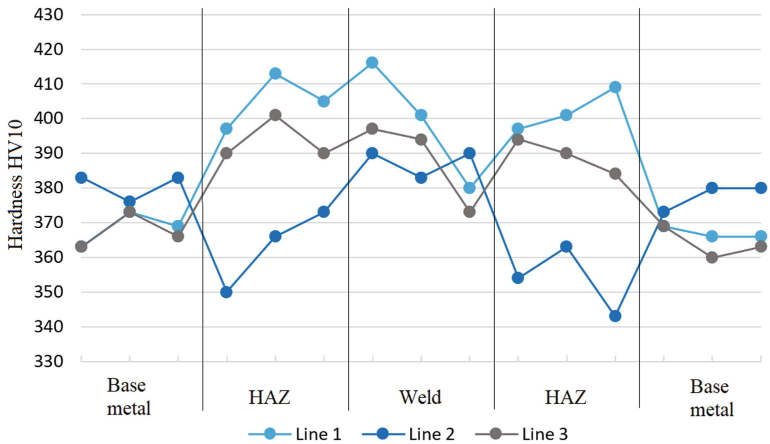

Fig. 7. Hardness distribution for weldments with Böhler alform 1100 L-MC.

the case of the use of Böhler alform 1100 L-MC wire. Since the $t_{8/5}$ cooling time was calculated to be around 5 s in all cases and the applied heat input was also similar, the differences caused by the different filler metals should be reflected in the weld metals hardness values. For a better comparison, the average, standard deviation, and standard deviation coefficient of the hardness of the weld metals are shown in Table 8.

Table 8. The average, standard deviation, and standard deviation coefficient values of the hardness of the weld metals

Filler metal	Place of the hardness tests	HV10	Standard deviation	Standard deviation coefficient [%]
Böhler Union X96	Line 1	401	24.10	5.99
	Line 2	382	7.21	1.89
	Line 3	402	22.90	5.70
	Average	395		
Böhler alform 1100 L-MC	Line 1	399	18.08	4.53
	Line 2	388	4.04	1.04
	Line 3	388	13.08	3.37
	Average	392		

According to Table 8, the results obtained show acceptable standard deviation and standard deviation coefficient of the hardness values. Based on the average hardness values measured in the welded joints, the two different (matching and undermatching) filler metals resulted in very similar weld metal hardness. The measured weld metal hardness was minimally higher for Böhler Union X96, but the difference was almost negligible.

4 Conclusion

Based on the investigations and their results, the following conclusions can be drawn.

1. The coarse-grained heat-affected zone (CGHAZ), the intercritical heat affected zone (ICHAZ), intercritically reheated coarse-grained heat-affected zone (ICCGHAZ) of the investigated Alform 1100M x-treme high strength steel was successfully simulated for three technological variants of gas metal arc welding (GMAW) in the range of $t_{8/5}$ = 5–30 s. The results of the hardness tests showed that, increasing of the cooling time has a negative effect on the hardness of the steel. In case of higher cooling time even the hardness of the CGHAZ did not reach the hardness of the base metal, the investigated high strength steel was softened on account of the welding heat cycles.
2. Thus, as the result of physical simulations on the examined material and recommendations in the literature, the chosen $t_{8/5}$ cooling time was 5 s.
3. Based on the chosen cooling time the parameters were calculated and tested for GMAW. For the welding experiments two different filler metals were chosen: Böhler Union X96 (undermatching condition) and Böhler alform 1100 L-MC (matching condition).
4. According to the optical microscope images, there were no visible differences in the microstructure of the welded joints and in the total width of the different parts of the HAZs due to the similar heat input and cooling times applied.

5. Based on the hardness tests the lowest hardness values were in the HAZ of the root in case of the use of Böhler alform 1100 L-MC wire. According to the average hardness values measured in the welded joints, the two different filler metals resulted in very similar weld metal hardness. The measured weld metal hardness was minimally higher in the case of Böhler Union X96, but the difference was almost negligible.
6. To obtain more comprehensive information of the mechanical properties of the joints, further tests (tensile, bending, instrumented impact test, as well as fracture mechanical investigations) will be required.

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