Influence of the filler material on the mechanical characteristics of structural steel GMAW and MCAW welded joints

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Abstract: The main objective of this paper is to get an accurate result of the mechanical characteristics of welded joints of structural steel performed with two different types of filler material, wire, which are characterized by: simple welding technology, low structural changes of the basic materials, as well as lower cost of welds. The whole research is conducted in accordance with European standards for welding. Research has been conducted on two standard plates made of constructive steel S355J2 + N Z15, with a thickness of 15mm, according to standard EN ISO 15614-1. Both plates are welded with solid wire and metal cored wire under the protection of a gas mixture based on argon, and the whole process is supported by standard documentation. Destructive tests have been performed to determine the welded joints' quality and influence of different filler materials, such as tensile test, impact test, and hardness test in the weld and heat-affected zone. The experimental results confirm that the gas metal arc welding of structural steel in the protection of inert gas with solid and metal cored wire is a procedure that ensures the quality and safety of welded joints and retention properties of the base material after the welding process.

Keywords: ARC WELDING, SOLID WIRE, METAL CORED WIRE, HEAT–AFFECTED ZONE, DESTRUCTIVE TESTING, MECHANICAL TESTING, WELDING TECHNOLOGY, TEST SPECIMENS

1. Introduction

Today's globalization is characterized by accelerated technical and technological development. As a part of mechanical engineering, welding has not been lagging in technological development, new welding techniques and technologies are constantly being introduced, resulting in reduced production costs, and improved technical characteristics of the welded joints [1]. The conventional joining process Gas Metal Arc Welding – GMAW is a widely used process for welding of structural steel in a number of engineering fields such as shipbuilding, civil construction, mining equipment and metallurgy [2]. Consequently, several innovations appear in this welding process that contribute to its improvement. One of the improvements is the semi-automatic welding process Metal Cored Arc Welding – MCAW, which uses continuously fed wire/ electrode as consumable with different flow ratios of inert and active gas. Although there are many common features between the two processes, there are also several fundamental differences, most notably the fact that MCAW operates over a wider range of shielding gases and offers more flexibility with alloy compositions than solid wire for MIG/MAG. In metal cored arc welding processes, the slag levels are low as compared to solid wire welding processes. The lack of slag makes welding easier, and mechanization allows for higher productivity, representing a good advantage over the GMAW.

Structural steel is the most used type of material in mechanical engineering and is usually welded by GMAW. The structural steel belongs to the group of ferritic steels, and its main division is based on mechanical characteristics [3]. The structural steel welded joint quality should meet the base material's mechanical characteristics, which are determined by mechanical testing.

Mechanical tests are a primary indicator that determines the mechanical properties of welded joints, and they can be done destructively and non-destructively [4]. The mechanical testing of the welded joints can be performed in two ways, on a fully welded structure or test pieces – test specimens made from a part of the welded structure, and the second way, laboratory test specimens prepared and made under the general conditions of welding in production, which they shall represent. The production of the test pieces - welded specimens must be carried out in accordance with the prescribed norms and standards for the welding procedure as well as the type of material, which is welded, while taking care that they are fully prepared and made under conditions that correspond to the production or assembly of the welded structure [7, 8].

In GMAW and MCAW, shielding gases play a fundamental role in arc characteristics, transfer mood and process stability and consequently affect the weld quality, while the type of the welding material is directly linked with the weld microstructure and its mechanical characteristics.

This paper aims to research the influence of two types of filler material, solid wire and metal cored wire, on the mechanical characteristics of welded joints of structural steel. Therefore, GMAW and MCAW welded joints on structural steel under protection of a gas mixture based on argon were performed. Destructive tests, such as tensile test, impact test, and hardness test were carried out in the weld and heat-affected zone to determine the welded joints' quality and its mechanical characteristics.

2. Materials and methods

2.1 Material

In this study, the base material is 15mm thick EN 10025-2 S355J2+N-Z15 structural steel, that is thermomechanical rolled with a ferrite-pearlite microstructure suitable for application under the 0 ^{o}C., with toughness of 24 J at - 20 ^{o}C. It has a minimum yield strength and according to standard ISO/TR 15608:2017 belongs to the group 1.2 with a range of 275 N/mm^2 < R_{eH} ≤ 360 N/mm^2 yield strength. A commercial solid AWS A5.18 ER 70S-6/ EN ISO 14341-B-G 49A 3 C S6 and metal cored AWS A5.18 E70C-6M H4/ EN ISO 17632-A T46 3 M M 2 H5 welding wires were selected, both with a diameter of 1.2 mm. The base material has a carbon equivalent value of maximum 0.40% ($CE_{IIW} = C + Mn/6 + (Cr + Mo + V)/5 + (Cu + Ni)/15$) and C ≤ 0,22 % representing good weldability without additional heat treatment process. The base material and filler wires chemical compositions and mechanical properties are shown in Table 1 and Table 2 respectively.

Table 1. *Chemical composition (%) of the steel and the welding wires according to mill certificate values*

	Structural steel EN 10025-2 S355 J2 +N Z15	Solid wire AWS A5.18 ER 70S-6	Metal cored wire AWS A5.18 E70C-6M H4
C	0.160	0.070	0.040
Si	0.260	0.880	0.610
Mn	1.200	1.460	1.420
P	0.019	0.009	0.011
S	0.005	0.006	0.025
Al	0.027	0.002	-
N	0.008	-	0.007
Cr	0.050	0.027	0.040
Cu	0.400	0.076	-
Ni	0.100	0.037	0.020
Ti	0.001	-	-
V	0.001	0.002	0.020
Mo	0.001	0.010	-
Nb	0.001	-	-
Fe	Bal.	Bal.	Bal

Table 2. *Mechanical properties of the steel and the welding wires according to mill certificate values*

	Structural steel EN 10025-2 S355 J2 +N Z15	Solid wire AWS A5.18 ER 70S-6	Metal cored wire AWS A5.18 E70C-6M H4
Yield strength R_{eH}, MPa	411	451	510
Tensile strength Rm, MPa	558	556	582
gation A5, %	18.5	31	27
Toughness, Impact test at -20 C	93	73	107

2.2 Preparation and welding

The preparation of the elements is carried out according to the European standards. From a sheet plate with dimensions 15 x 2050 x 5900, 4 plates with dimensions of 155 x 355 mm were cut by thermal process. According to standard EN ISO 15614-1, the HAZ of the thermal process must be machined off, and they were machined to a dimension of 150 x 350 mm and used to form a 15 x 300 x350 mm weld plate. Both plates were one-sided welded with the joint preparation symbol “Y”, with 60^{o} angle, 3 mm gap and 2 mm gap height according to standard EN ISO 9692-1. In order to limit the gap, two blocks of the same material were welded on either side of the plate and used as start and stop points outside the main plate.

The plates are welded by a certificated welder in PA position in an indoor environment with + wire polarity and M2-1 gas according to EN ISO 14175 containing 82% Ar and 18% CO_2., at a flow rate of 20 l/min. Welding plates were accomplished in 4 welding passes, the first pass of solid and two passes of metal-cored wires were performed with a Miller Axcess 450 CE W/ RMD power supply and an Axcess 40V wire feeder, while for other passes ESAB OrigoTMMIG 502cw power supply and OrigoTMFeed 304 wire feeder were employed. Before each welding pass, the slag is cleaned by grinding for better application of the next welding pass. The welding parameters of both plates are presented in Table 3. These parameters were selected for obtaining a stable process and formation of visual acceptable weld.

Table 3. *Welding parameters used for GMAW and MCAW welds*

2.3 Testing

According to standard EN ISO 15614-1 with aiming to determine the quality of welded plates and their mechanical properties, destructive and non-destructive testing after the welding process should be carried out. Therefore, non-destructive testing was performed before the destructive testing and no defects were detected. Mechanical evolution of the GMAW and MCAW welded joints was performed by tensile, impact and hardness testing of test specimens. The welded plates were sufficient in size to produce all the required test specimens and their locations are shown in Figure 1.

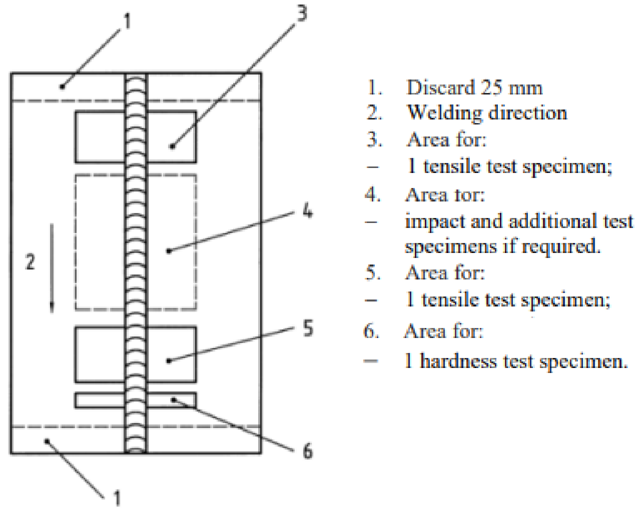


Fig. 1. *Location of test specimens for a butt joint in plate [5]*

Cross-weld tensile testing was performed based on EN ISO 4136 using the standard specimen dimension and geometry [6]. Two tensile test specimens were taken from each welded plate and marked with 1-3, 1-6 for GMAW weld and 2-3, 2-6 for MCAW weld. The specimens' thickness was equal to the base material, while the root and face side of the weld were not machined.

The Charpy impact test was performed according to ISO 6019 with standard specimen dimensions of 55 x 10 x 10 mm and the standard V-notch type geometry [7]. Three sets with three test specimens from three locations were taken; one with the notch located in the weld metal center, one positioned at the FL and one in the base material. All test specimens were performed at – 20 ^{o}C and marked with 1 for GMAW weld and 2 for MCAW weld.

Vickers hardness test (HV5) was performed with a test load of 49,03 N according to standard ISO 9015-1 [8]. The surface test was polished and etched and the measurements were made in two rows, one below the weld face and one from the root side at a depth of < 2mm. Three areas were covered in each row, the weld metal, the HAZ and base material and 3 individual indentations were taken in each area.

Arc welding process	Welding pass	Wire diameter, mm	Current parapmetars				Welding speed, mm/min	Wire feed rate, m/min	Line energy input, kJ/mm
			Amperage, A	Voltage, V	Type	Poliarty			
GMAW	1	1.2	90-100	17-18	DC	(+)	160-200	4.7	0.72
	2	1.2	230-245	25.5-27	DC	(+)	250-300	8	1.74
	3, 4	1.2	250-260	26.5-28	DC	(+)	260-320	9	1.82
MCAW	1	1.2	80-90	17.5-18	DC	(+)	140-180	5	0.67
	2	1.2	235-245	27-27.5	DC	(+)	240-290	9	1.63
	3	1.2	260-270	28-28.5	DC	(+)	250-300	11	1.74
	4	1.2	250-260	28-28.5	DC	(+)	250-300	10.5	1.68

3. *Results and discussion*

From each welding joint was submitted to two tensile test specimens. Figure 2 shows the good tensile strength of the welds, reaching at least 410MPa yield strength and 540MPa ultimate tensile strength, exceeding the strength of the base material, resulting in failure at the BM. These results were considered satisfactory.

Fig. 2. *Tensile test specimens after testing*

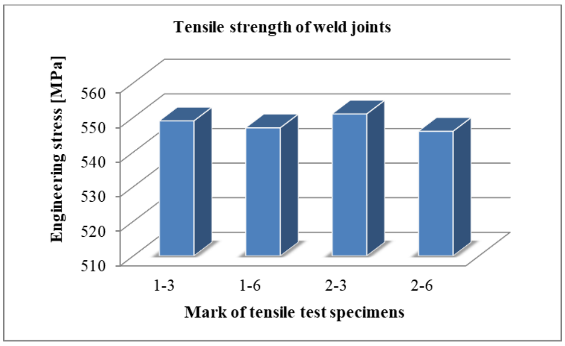


Fig. 3. *Tensile strength of weld joints*

Visual inspection can observe elongation in the HAZ and a clear fusion line between the base material and the weld metal after tensile testing. Due to the slightly higher amount of heat input in the GMAW weld, there is a solid melting of the base material edges and a complete mixing of the base and filler material. On the other hand, in the MCAW welded joint, a lack of fusion can be observed with the sidewalls, Figure 2. Generally, the tensile strength is reduced with increasing heat input due to microstructure and the possibility of larger grains. The results in Figure 3 show a slightly higher tensile strength among the MCAW weld joints compared to GMAW weld joints.

The Charpy impact test results are presented in Table 4 and 5. Despite the fact that there is a large difference in toughness between the base material and weld metal, all welds provide an acceptable toughness of >27 J at -20 ^{o}C. The GMAW weld joint is characterized with a higher toughness in the weld metal zone and increased plasticity and reduced brittleness compared to the MCAW weld joint. The higher toughness of the GMAW weld joint was achieved as a result of higher heat input and its more uniform distribution leading to slower cooling rates and a softer microstructure. However, excessively high heat input can result in detrimental toughness, especially in the HAZ, due to very large grains and unfavorable microstructure [9].

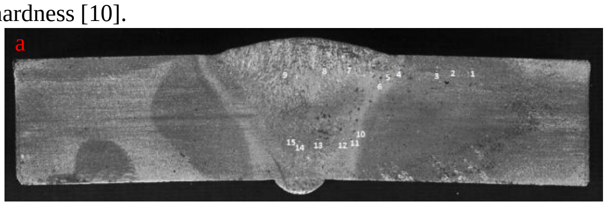
Table 4. *The Charpy impact test results of GMAW weld joint*

Location	GMAW weld joint			
	Mark of test specimens	Temperature testing, C	Toughness, J	Average touqhness, J
Base material	1-1	-20	121	106
	1-2	-20	91	
	1-3	-20	106	
Heat affected zone	1-4	-20	106	95
	1-5	-20	84	
	1-6	-20	95	
Weld metal	1-7	-20	99	84
	1-8	-20	59	
	1-9	-20	94	

Table 5. *The Charpy impact test results of MCAW weld joint*

Location	MCAW weld joint			
	Mark of test specimens	Temperature testing, C	Toughness, J	Average touqhness, J
Base material	2-1	-20	116	103
	2-2	-20	101	
	2-3	-20	92	
Heat affected zone	2-4	-20	78	80
	2-5	-20	73	
	2-6	-20	89	
Weld metal	2-7	-20	46	51
	2-8	-20	49	
	2-9	-20	58	

In Figure 4 are presented the indentation locations of both weld joints, while Figure 5 shows the measured Vickers hardness HV5 in the two rows, the face and the root of the weld. It can be seen that higher hardness values were found in the weld metal, especially in the weld face, as a result of more intensive heat removal and normalization of the previous weld pass with the next one. However, the measured hardness in all zones is not critical and is within an acceptable value. Post-weld heat treatment can result in a more positive microstructure and lower hardness [10].



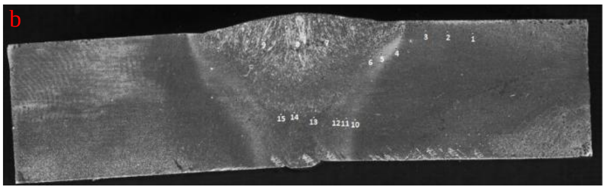


Fig. 5. Location of indentation for Vickers hardness test, GMAW weld joint (a); MCAW weld joint (b)

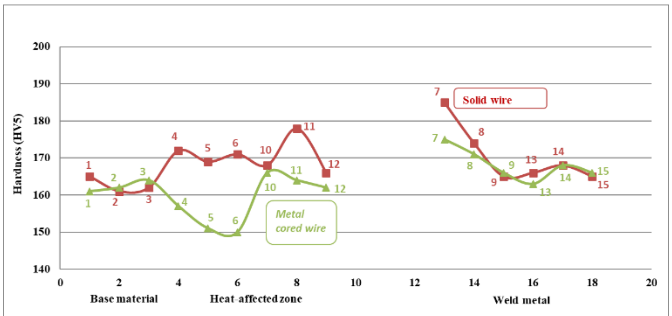


Fig. 6. Measured values of Vickers hardness test HV5

4. Conclusions

In this work, 15 mm – thick structural steel in quality S235J2 was successfully welded with two types of filler material, solid and metal cored wire, under protection of a gas mixture based on inert gas – argon. In general, the presented results show a good quality and safety of welded joints, in accordance with European standards for welding. The most important conclusions of the work are the following:

- The mechanical characteristics of both welded joints are perfect. The tensile strength of the welds is above the base material strength while the toughness of the GMAW weld joint is higher compared to the MCAW weld joint, especially in the weld metal due to the higher heat input and slower cooling rate. The toughness of the MCAW weld metal can be increased with pre-heat treatment of the base material or post-weld heat treatment.
- In terms of hardness, its values increased continuously from the base material towards the weld metal. The measured values are acceptable for both weld joints, post-weld heat treatment can be used in order to reduce the brittle, especially in the MCAW weld joint, which occurs as a result of a higher cooling rate.
- The best aesthetic appearance of the weld is produced by metal cored wire by spray transfer mode, thereby contributing to higher productivity compared to solid wire which causes more spatter and less deposit of filler material.
- In the GMAW the less deposit of filler material results in a minimally reduced productivity, but provides a more affordable microstructure of the welded joint due to slower cooling rate, that is represented through the GMAW weld joint toughness.
- Due to the smaller metal cross-sectional area of the metal cored wire, compared to the same diameter of solid wire, at the same welding current, the melting rate of metal cored wire is significantly higher, thus the wire feed rate and speed of welding are higher, but they should be controlled for the stability of the process.

The experimental results confirmed that the gas metal arc welding of structural steel in the protection of inert gas with solid and metal cored wire is a procedure that ensures the quality and safety of welded joints and retention properties of the base material after the welding process.

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