INFLUENCE OF THE METAL CORED AND FLUX CORED WIRE ON THE STRUCTURAL STEEL WELDED JOINTS

M. Petreski[1,*], D. Runchev[1], G. Vrtanoski[1], A. Krstevska[1]

[1]University „Ss. Cyril and Methodius", Faculty of Mechanical Engineering, Rugjer Boshkovikj 18, P.O. Box 464, MK-1000 Skopje, Republic of North Macedonia

E-mail: martin.petreski@mf.edu.mk

Abstract

The main objective of the research covered in this paper is to get a precise result of the mechanical characteristics of welded joints of structural steel performed with two different filler materials, flux cored wire and metal cored wire, that are characterized by: low structural changes of the basic materials, high mechanical properties, simple welding technology, as well as lower cost of welds. The whole research is conducted in accordance with European welding standards. Research has been undertaken indoors on two standard steel plates in quality S355J2 +N Z15, with a thickness of 15 (mm), according to standard EN ISO 15614-1. The whole process is supported by standard documentation, where welding with the metal cored wire is performed under the protection of a gas mixture based on argon, while for flux cored wire is used active CO_2 gas as a shielding gas. To determine the welded joints' quality and influence of different filler materials, destructive tests, such as impact test, tensile test, and hardness test in two zones, the weld and heat-affected zone, have been carried out. The experimental results confirm that the gas metal arc welding of structural steel in the protection of inert or active gas with metal or flux cored wire ensures the quality and safety of welded joints and retention properties of the base material after the welding process. Both processes have their advantages and disadvantages, and the choice between them will depend on the project requirements and the welder's preferences.

Keywords: flux cored wire, metal cored wire, mechanical testing, welding technology, heat-affected zone

1. Introduction

Today's globalization is characterized by accelerated technical and technological development. Understanding the intricate relationship between globalization and technological development is crucial to navigating the challenges and harnessing the opportunities that lie ahead. 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, 11]. Consequently, several innovations appear in this welding process that contribute to its improvement. One of the improvements are the semi-automatic welding processes Metal Cored Arc Welding – MCAW and Flux Cored Arc Welding - FCAW, which use 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, FCAW utilize a tubular wire filled with a flux compound that provides the necessary shielding gases, alloying elements, and slag-forming agents during the welding process, while MCAW consist of a metal sheath filled with powdered metal alloy, which requires external shielding gas to protect the weld pool from atmospheric contamination. In MCAW processes, the slag levels are low as compared to FCAW processes, that leads to improved productivity, reduced spatter, and better overall weld quality. On the other hand, the self-shielding feature of FCAW allows for greater adaptability to different environments, making it a preferred choice for outdoor applications and those involving materials with higher levels of contaminants. Structural steel is the most used type of material in mechanical engineering and is usually welded by GMAW process or its improvments, MCAW and FCAW processes. 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 [11]. 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 FCAW or MCAW process, 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 [11, 12]. This paper aims to research the influence of two types of filler material, rutile flux cored wire and metal cored wire, on the mechanical characteristics of welded joints of structural steel. Therefore, FCAW and MCAW welded joints on structural steel under protection of active CO_2 gas i.e. 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

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°C., with toughness of 27 (J) at - 20 (°C). It has a minimum yield strength of 355 (N/mm^2) and according to standard ISO/TR 15608:2017 belongs to the group 1.2 with a range of 275 (N/mm^2) < ReH ≤ 360 (N/mm^2) yield strength. A rutile flux cored AWS A5.20 E71T-1M-J/ EN ISO 17632-A T46 3 P M 1 H5 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% (CEIIW = 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	Flux cored wire EN ISO 17632-A T46 3 P M 1	Metal cored wire EN ISO 17632-A T46 3
C	0.160	0.040	0.040
Si	0.260	0.440	0.610
Mn	1.200	1.400	1.420
P	0.019	0.013	0.011
S	0.005	0.010	0.025
Al	0.027	-	-
N	0.008	0.006	0.007
Cr	0.050	0.040	0.040
Cu	0.400	-	-
Ni	0.100	0.040	0.020
Ti	0.001	0.100	-
V	0.001	0.010	0.020
Mo	0.001	-	-
Nb	0.001	0.020	-
Fe	Bal.	Bal.	Bal.

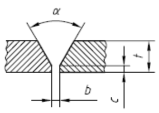
Table 2. Mechanical properties of the steel and the welding wires according to mill certificate values

	Structural steel EN 10025-2 S355 J2 +N Z15	Flux cored wire EN ISO 17632-A T46 3 P M 1 H5	Metal cored wire EN ISO 17632-A T46 3 M M 2 H5
Yield strength ReH, MPa	411	569	510
Tensile strength Rm, MPa	558	618	582
Elongation A5, %	18.5	26	27
Toughness, Impact test at -20 C	93	64	107

2.2 Preparation and welding

Proper preparation of weld plates is crucial to achieving strong, durable, and high-quality welds. Inadequate preparation can lead to various welding defects, such as porosity, lack of fusion, and inclusions. Therefore, the preparation of the welding elements is carried out in accordance with European standards. From a sheet plate with dimensions 15 x 2050 x 5900 (mm), 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. By maching one side of the plate is beveled to appropriate angle to create the required groove for the weld, symbol "Y", with 60^o angle, 3 (mm) gap width and 2 mm gap height according to standard EN ISO 9692-1, Table 3. In order to limit the gap and maintain proper alignment, two blocks of the same material were tack welded on either side of the plate and used as start and stop points outside the main plate.

Table 3. Preparing of the groove according to EN ISO 9692-1 [9]

Material	Material thickness t mm	Type of preparation	Symbol (in acc. with ISO 2553)	Cross - section	Dimensions			Weld illustration
					Angle α	Gap b mm	Thickness of root face c mm	
S355J2+N	5 ≤ t ≤ 40	Single - V preparation with broad root face	Y		α = 60	1 ≤ b ≤ 4	2 ≤ c ≤ 4	

Both plates are welded by a certificated welder in PA postion in an indoor environment with (+) wire polarity. The plate welded by flux cored wire was accomplished in 5 welding passes with both sides weld due to the humping and incomplete penetration while performing the first – root pass. After completing of all four passes from one side, the last fifth pass is performed from the other side of the plate with a high welding current to melt the first pass that is of unacceptable quality. The flux generates slag, a vitreous layer that covers the weld bead and protects it from atmospheric contamination during cooling. This slag continas impurities that are not compatible with argon gas. Therefore, as a shielding gas is used active CO_2 gas with mark C1 according to EN ISO 14175 containing 100% CO_2, at a flow rate of 20 (l/min). All passes were performed with an ESAB OrigoTMMIG 502cw power supply and OrigoTMFeed 304 wire feeder. Before each welding pass, the slag is cleaned by grinding for better application of the next welding pass. The plate welded by metal cored wire was one-side welded in 4 welding passes, under protection of a gas mixture based on inert gas – argon with mark M2-1 gas according to EN ISO 14175 containing 82% Ar and 18% CO_2, at a flow rate of 20 (l/min). The first 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 4. These parameters were selected for obtaining a stable process and formation of visual acceptable weld.

Table 4. Welding parameters used for FCAW and MCAW welds

Arc welding process	Welding pass	Wire diameter, mm	Current parapmetars				Welding speed, mm/min	Wire feed rate, m/min	Line energy input,
			Amperage, A	Voltage, V	Type	Poliarty			
FCAW	1	1.2	110-130	20.5-21	DC	(+)	160-200	6.5	0.84
	2, 3	1.2	230-250	28-29	DC	(+)	250-300	12.5	1.61
	4	1.2	205-225	28-28.5	DC	(+)	240-280	11.5	1.54
	5	1.2	240-250	29-30	DC	(+)	260-320	12.5	1.68
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

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 assessment of the FCAW and MCAW welded joints was performed by tensile, impact and hardness testing of test specimens [11]. The welded plates were sufficient in size to produce all the required test specimens and their locations are shown in Figure 1.

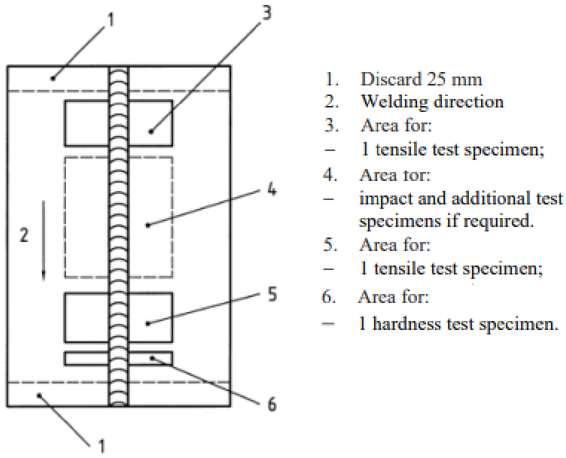


Figure 1. Location of test specimens for a butt joint in plate [5]

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 2-3, 2-6 for MCAW weld and 3-3, 3-6 for FCAW 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 2 for MCAW weld and 3 for FCAW 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 < 2 (mm). An additional row in the middle of the weld was performed in the flux cored wire welded plate in order to test the influence of the last fifth weld pass. Three areas were covered in each row, the weld metal, the HAZ and the base material, and 3 individual indentations were taken in each area.

3. Results and discussion

Two tensile test specimens were submitted from each weld joint. Figure 2 shows the good tensile strength of the welds, reaching at least 410 (Mpa) yield strength and 550 (Mpa) ultimate tensile strength, exceeding the strength of the base material, resulting in BM failure. These results were considered satisfactory. Figure 2.

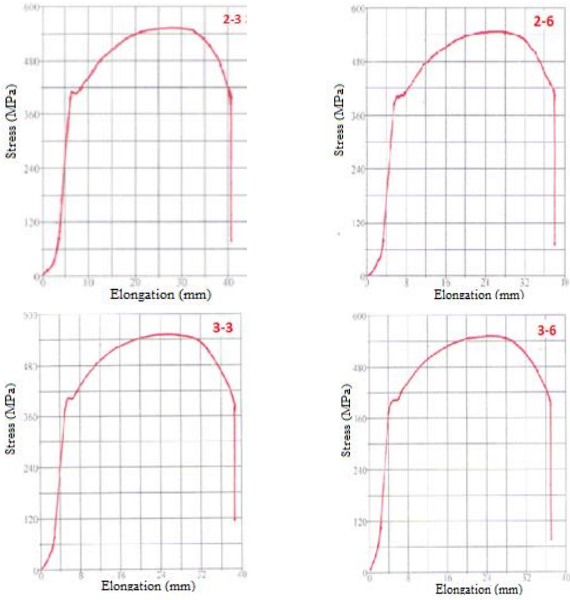


Figure 2. Stress – elongation curve of the tensile test specimens

After tensile testing, a visual inspection can observe the HAZ elongation and a clear fusion line between the base material and the weld metal. In both welds, the MCAW and the FCAW weld, a lack of fusion with the sidewalls can be noticed due to the lower heat input than standard GMAW, Figure 3.

Figure 3. Tensile test specimens after testing

Generally, the tensile strength is reduced with increasing heat input due to microstructure and the possibility of larger grains [11]. The stress-elongation curves show the same tensile strength in all tensile test specimens. The Charpy impact test results are presented in Table 5, and Figure 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). In both plates, the toughness results of the weld meal showed lower toughness than for the HAZ and base material due to higher cooling rates leading to the formation of a brittle microstructure in the weld metal. The MCAW weld joint is characterized by slightly high toughness and reduced brittleness compared to the FCAW weld joint.

Besides the same heat input, the lower toughness of the FCAW weld joint results from the use of the active shielding gas CO_2 that causes additional cooling during the welding process.

Table 5. Charpy impact test results of MCAW and FCAW weld joints

Location	MCAW weld joint				FCAW weld joint			
	Mark of test specimens	Temperature testing , C	Toughness, J	Average touqhness, J	Mark of test specimens	Temperature testing , C	Toughness, J	Average touqhness, J
Base material	2-1	-20	116	103	3-1	-20	103	98
	2-2	-20	101		3-2	-20	96	
	2-3	-20	92		3-3	-20	95	
Heat affected zone	2-4	-20	78	80	3-4	-20	67	78
	2-5	-20	73		3-5	-20	80	
	2-6	-20	89		3-6	-20	87	
Weld metal	2-7	-20	46	51	3-7	-20	33	35
	2-8	-20	49		3-8	-20	41	
	2-9	-20	58		3-9	-20	31	

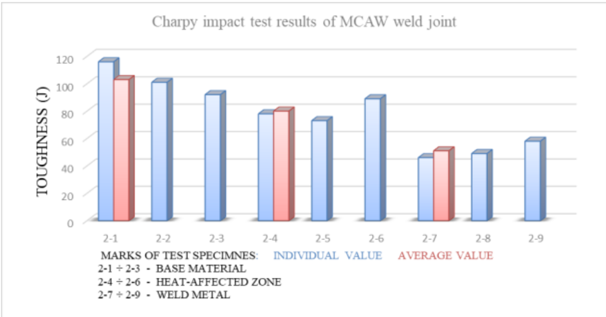


Figure 4. Graphic display of Charpy impact test results of MCAW weld joint

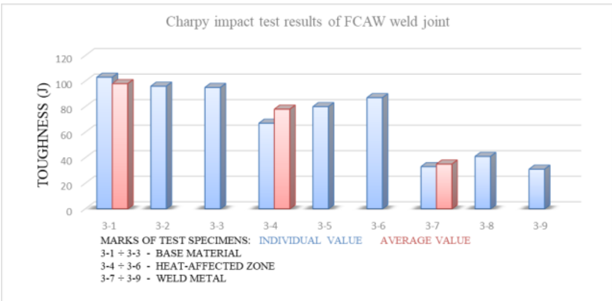


Figure 5. Graphic display of Charpy impact test results of FCAW weld joint

In Figure 6 are presented the indentation locations of both weld joints, while Figure 7 shows the measured Vickers hardness HV5 in the two i.e. three rows, in the face, root and middel of the weld. The hardness results shown that the greatest infulence on hardness has the cooling rates. The highest hardness values were found in the weld metal, especially in the final weld pass, due to the intensive cooling rate and missing of the next weld pass that normalizes the previous one. This fact is particularly emphasized in the last – fifth weld pass of FCAW weld joint as a result of using the active shielding gas CO_2. 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, 11].

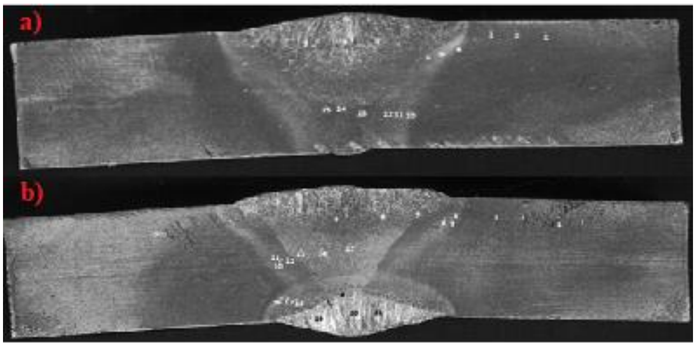


Figure 6. Location of indentation for Vickers hardness test,
a) MCAW weld joint; b) FCAW weld joint

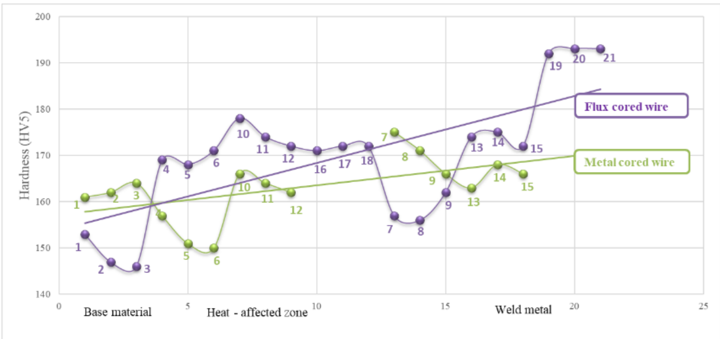


Figure 7. Measured values of Vickers hardness test HV5

4. Conclusions

Based on the present experimental results the following conclusions can be drawn:

- The experimental results show that 15 (mm) – thick structural steel in quality S355J2+N Z15 can be successfully welded with two types of filler material, metal and rutile flux cored wire, under protection of a gas mixture based on inert gas – argon or active gas.
- The mechanical characteristics of both welds are above the base material characteristics within the acceptance criteria in accordance with European standards.
- The tensile strengths of welds are on the same level with yield strength > 410 (MPa), but a visual inspection can observe a lack of fusion with the sidewalls due to lower heat input.
- The toughness of FCAW weld joint is lower compared to the MCAW weld joint due to the use of the active shielding gas CO_2 that leads to higher cooling rates and formation of a brittle microstructure in the weld metal. The rutile flux cored wire generates slag that protects the weld bead from atmospheric contamination and by removing the shielding gas, the cooling rates can be decreased, leading to toughness improvement.

- The hardness 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 to reduce the brittle, especially in the FCAW weld joint, which occurs due to higher cooling rates.
- The disadvantage of FCAW process over the MCAW is removing the slag after each welding pass, thereby contributing to lower productivity and possibility of making welding errors if the welder has not enough experience of this type of filler material.

5. References

[1] Agrawal B.P. and Kumar R. (2016). Challenges in application of pulse current gas metal arc welding process for preparation of weld joint with superior quality. *International Journal Engineering Research Technology*, 5, 319–327.

[2] Pal K. and Pal S.K. (2011). Effect of pulse parameters on weld quality in pulsed gas metal arc welding: a review. *Journal. Material. Engineering Perform.*, 20, 918–931.

[3] Balakrishnan M., et al. (2022). Post fire tensile properties of S355J2 structural steel welded connections for construction industrial applications. *Metallurgical Research and Technology*. 119 (551), 1-17.

[4] Germanischer Lloyd Aktiengesellschaft. (2000). Rules for Classification and Construction - Materials and Welding. Hamburg, Germany.

[5] International Organization for Standardization. (2017). *ISO 15614-1:2017 Specification and qualification of welding procedures for metallic materials — Welding procedure test — Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloy*s.

[6] International Organization for Standardization. (2012). *ISO 4136:2012 Destructive tests on welds in metallic materials — Transverse tensile test*.

[7] International Organization for Standardization. (2022). ISO *9016:2022 Destructive tests on welds in metallic materials — Impact tests — Test specimen location, notch orientation and examination*.

[8] International Organization for Standardization. (2011). *ISO 9015-1:2011 Destructive tests on welds in metallic materials — Hardness testing — Part 1: Hardness test on arc welded joints*.

[9] International Organization for Standardization. (2013). *ISO 9692-1:2013 Welding and allied processes – Types of joint preparation – Part 1: Manuel metal arc welding, gas – shielded metal arc welding, gas welding, TIG welding and beam welding steels.*

[10] Nguyen T.C., Weckman D.C. and Johnson D.A. (2007). The discontinuous weld bead defect in high-speed gas metal arc welds. *Weld Journal*, 86, 360-372.

[11] Petreski M., Runchev D., Vrtanoski G. (2022). Influence of the filler material on the mechanical characteristics of structural steel GMAW and MCAW welded joints. technology. *Technological basis of "Industry 4.0"*, 16, 312-315

[12] Bajič N., .Bajič D., Veljič D., Rakin M. (2013). Advantage of use activated flux-cored wire instead of solid wire with the MAG welding process from the mechanical properties aspect. *Metabk*, 52, 453-456.