COMPARATIVE ANALYSIS OF THE QUALITY OF WELDED JOINTS OF DUPLEX STEEL 1.4462 MADE BY ELECTRIC ARC METHODS

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Abstract

The topic of this paper is the analysis and comparison of the effects of welding austenitic-ferritic (duplex) corrosion-resistant steel 1.4462 with a thickness of 4 mm using manual metal arc welding (MMAW) and shielded metal arc welding (SMAW). The mentioned class of steel is widely represented in many branches of industry: food, oil, construction, medicine, etc. Therefore, it is very important to recognize reliable, efficient, and cost-effective joining procedures. The paper is based on the experimental analysis of the joints obtained using conventional arc welding technologies. The analysis of the quality of the welded joints was carried out by testing the impact toughness using the Charpy method, testing the strength of the material by tension, and testing the microhardness. Special emphasis is given to testing impact toughness using an instrumented Charpy pendulum. On the basis of the obtained results, a detailed analysis of the quality of the welded joints was carried out in terms of the relationship between the energy of initiation (E_i) and the energy of propagation (E_p) of the crack and their share in the total fracture energy (E_u). Tests confirm the rationality and advantage of applying the SMAW welding procedure in the function of the reliability of the welded joint.

Keywords: duplex steel, MMAW, SMAW, impact toughness, fracture energy

1. Introduction

Duplex steel has been using almost for a century and expansion of its usage in an increasing number of branches of industry is obvious. They are used in thermoenergetics, process industry, food and medicine industry, construction etc. Although they are resistant to complex high-intensity loads, their weldability is limited. The mechanical characteristics of the welded joints should be better or equal with characteristic of the basic material (BM).

Duplex stainless steels consist equal proportions of austenitic and ferritic phase (50 – 50%). Although they were produced quite early (30s of the XX century) they were not commercially available until the 80s of the XX century. Reasons for that were as follows: poor corrosion resistance, low strength and poor weldability [1,2,3]. Nowadays, duplex stainless steels combine the best characteristics of ferritic and austenitic structure thanks to alloy elements, whose additional role is to stabilize the phases: nitrogen, nickel, molybdenum, tungsten, copper, silicon.

Large impact on intensive work with duplex steels and their development had maritime and process industry. The general properties that recommend them for use are higher strength, exceptional corrosion resistance, good weldability, lower and more stable prices on the market. When it comes to the mechanical properties of duplex stainless steels, they are significantly better than austenitic and ferritic steels individually. Austenite provides high toughness at low temperatures and high resistance to general corrosion, while ferrite increases strength and resistance to hot cracking and stress corrosion cracking [4].

The transition from ductile to fragile fracture is gradual. Because duplex stainless steels are two-phase and have a lamellar structure, the way of their shaping and manufacturing greatly affects the mechanical characteristics. The field of their exploitation is generally even with other stainless steels, but these are additionally used in "extreme" conditions.

The problem of weldability of austenitic-ferritic steels is the question of maintaining the ratio of austenitic and ferritic phases (50-50%) in the weld metal (WM). It was only in the 80s of the last century that the importance of nitrogen alloying began to be obviously seen. Due to the lack of nitrogen, the ferritization of the structure occurs, which implies reduced mechanical and corrosion characteristics and a decrease in their weldability. The welding of duplex steel is based on preserving the balance of the austenitic and ferritic phases. Therefore, when welding these steels, three parameters must be taken into account: the specification of the BM - on the limit content of nitrogen, the amount of heat introduced in the welded joint and thermal treatment after welding thicker elements [2,3].

Welded joint of duplex steel solidifies as 100% ferritic while austenite forms and grows in the solid state [5]. Because of that is important to remember that nitrogen and nickel are the main elements responsible for sustaining gamma phase and chromium and molybdenum for alpha phase. Required characteristics of the welded joint could be gotten by optimal parameters of welding. These parameters are classified into two groups [1, 3]:

1. thermal-energy parameters – preheating, input heat, electric arc energy, cooling dynamics,
2. physical-chemical parameters – composition of the BM, type of additional material, protective atmosphere and degree of mixing.

The specification of the BM is stated as a parameter that dictates the chemical composition of the additional material and primarily the amount of nitrogen and nickel. Nitrogen is found in the appropriate measure, defined by the standard, in the BM, and the proportion of nickel is increased in the additional material. If there is not enough nitrogen, it will be trapped in the ferrite phase. If we add a smaller amount of introduced heat to that, nitrogen will not be able to find its way to the austenite phase, the initiation of which will be initiated by the nickel from the additional material. In this way, the ferrite phase remains dominant and chromium nitrides are formed in the form of precipitates. However, if there is enough nitrogen in the BM, in the addition material of nickel, an austenite lamellar phase will form in part of the ferrite grains, which will be interrupted in this way, improving the mechanical and corrosion properties of the welded joint [5].

2. Basic and additional material

Basic material used in the test is corrosion resistant duplex steel 1.4462 (DIN X2CrNiMoN 22-5-3). Chemical composition of the steel 1.4462 is given in Table 1, and its mechanical properties in Table 2.

Table 1. Chemical composition of the material 1.4462

Main alloying additions (wt.%)											
C	Si	Mn	P	S	Cr	Ni	Mo	Nb	Cu	Co	N
0.017	0.31	1.34	0.028	0.001	22.29	5.66	3.16	0.004	0.23	0.13	0.168

Table 2. Mechanical properties of material 1.4462

Yield strength, $R_{p0,2}$, MPa	Tensile strength, R_m, MPa	Elongation, A_5, %	Hardness, HB	Impact thougness, K_v, J/cm^2
647	832	34	264	238

The 1.4462 steel is a combination of the best characteristics of austenitic and ferritic steels. It is widely used in aggressive environments. The weldability of the material is good and no preheating or subsequent heat treatment is required. This steel is resistant to high temperatures and has a low coefficient of thermal expansion, which implies a minimum of residual stresses. This steel stands out for its resistance to pitting, stress and intercrystalline corrosion [6,7]. Corrosion-resistant duplex steel 1.4462 is magnetic.

According to the recommendation [7], for steel 1.4462, the maximum temperature of the intermediate passage is 150 ÷ 250 °C, and the energy of the electric arc is 0.5 ÷ 3.5 kJ/mm.

The additional material for MMAW is coated rutile-basic electrode INOX R 22/9/3 LN (EN 1600: E 22 9 3 N L) produced by Elektrode Jesenica, Slovenia. According to the manufacturer's recommendation, the electrode is recommended for welding duplex stainless steel using direct polarity current. Before use, the electrode must be dried for 2 hours at 300 °C. The chemical composition of the INOX R 22/9/3 LN electrode is given in Table 3, and its mechanical properties in Table 4. A ∅3.25 mm electrode was used for welding, and the welding current is in the interval 70 ÷ 125 A.

Table 3. Typical chemical composition of all-weld-metal of INOX R 22/9/3 LN

Main alloying additions (wt.%)						
C	Si	Mn	Cr	Ni	Mo	N
≤0.03	≤0.9	0.8	23	9	3.2	0.17

Table 4. Mechanical properties of all-weld-metal of INOX R 22/9/3 LN

Yield strength, $R_{p0,2}$, MPa	Tensile strength, R_m, MPa	Elongation, A_5, %	Toughness (on +20 °C), A_v, J
>540	680-890	>22	>47

A solid wire electrode G/W 22 9 3 NL (ISO 14342-A) with a diameter of 1 mm was used for SMAW welding. The metal of welded joint obtained by this electrode is corrosion resistant and has good mechanical properties. The chemical composition of the solid wire electrode is given in Table 5, and its mechanical properties in Table 6.

Table 5. Typical chemical composition of all-weld-metal of G/W 22 9 3 NL

Main alloying additions (wt.%)															
C	Si	Mn	P	S	Cr	Mo	Ni	Nb	Cu	Ti	Al	Co	N	B	V
0.01	0.52	1.44	0.018	0.0005	23.2	3.44	8.2	0.01	0.07	0.01	0.006	0.02	0.13	0.002	0.05

Table 6. Mechanical properties of all-weld-metal of G/W 22 9 3 NL

Yield strength, $R_{p0,2}$, MPa	Tensile strength, R_m, MPa	Elongation, A_5, %
450	550	20

3. Welding of samples

Dimensions of welded samples are 360×240×4 mm. The length of welded joint is 360 mm. For welding the samples with the MMAW and SMAW methods, the sides of the joint were prepared in the form of a V groove (Figure 1).

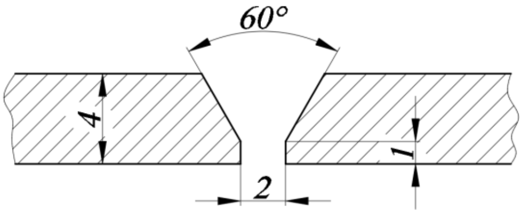


Figure 1. Preparation of the V groove

A TIG 220 DC HF FV device was used for MMAW (111) welding. Welding was done in two passes. The temperature of the intermediate passage is 150 °C. Welding parameters are given in Table 7.

Table 7. Parameters of MMAW welding

	Arc voltage, *U*, V	Welding current, *I*, A	Welding speed, *v*, cm/min
root weld pass	22	72	30
second weld pass	24	85	30

Due to the small thickness of the sheet, the welded joint was realized in two sequences (Figure 2). First, the part from the middle to the end (sequence I) was done, and sequence II from the end to the middle. The appearance of the welded joint is shown in Figure 3.

For SMAW (135) welding, the device VARSTROJ - VARMIG 600 D44 Synergy TIG 220 DC HF FV was used. Welding was done in two passes. The shielding gas used is EN ISO 14175: M13. The temperature of the intermediate passage is 150 °C. The welding parameters are shown in Table 8. The appearance of the welded joint is shown in Figure 4.

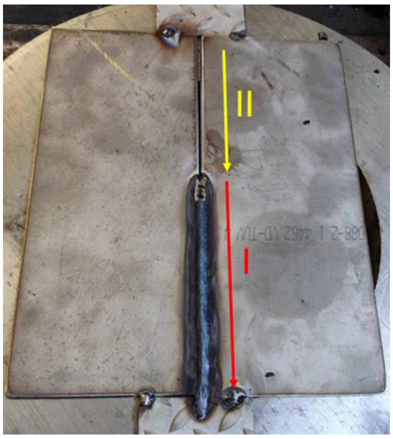


Figure 2. Forming joint in two sequences

Figure 3. The appearance of the welded joint (face and root)

Table 8. Parameters of SMAW welding

	Arc voltage, *U*, V	Welding current, *I*, A	Welding speed, *v*, cm/min	Shielding gas flow, l/min
root weld pass	23	135	35	17
second weld pass	24.8	167.4	35	17

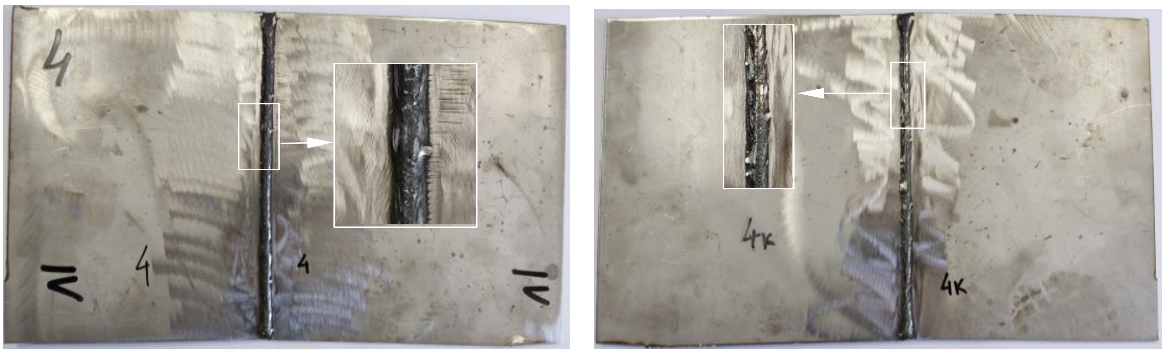
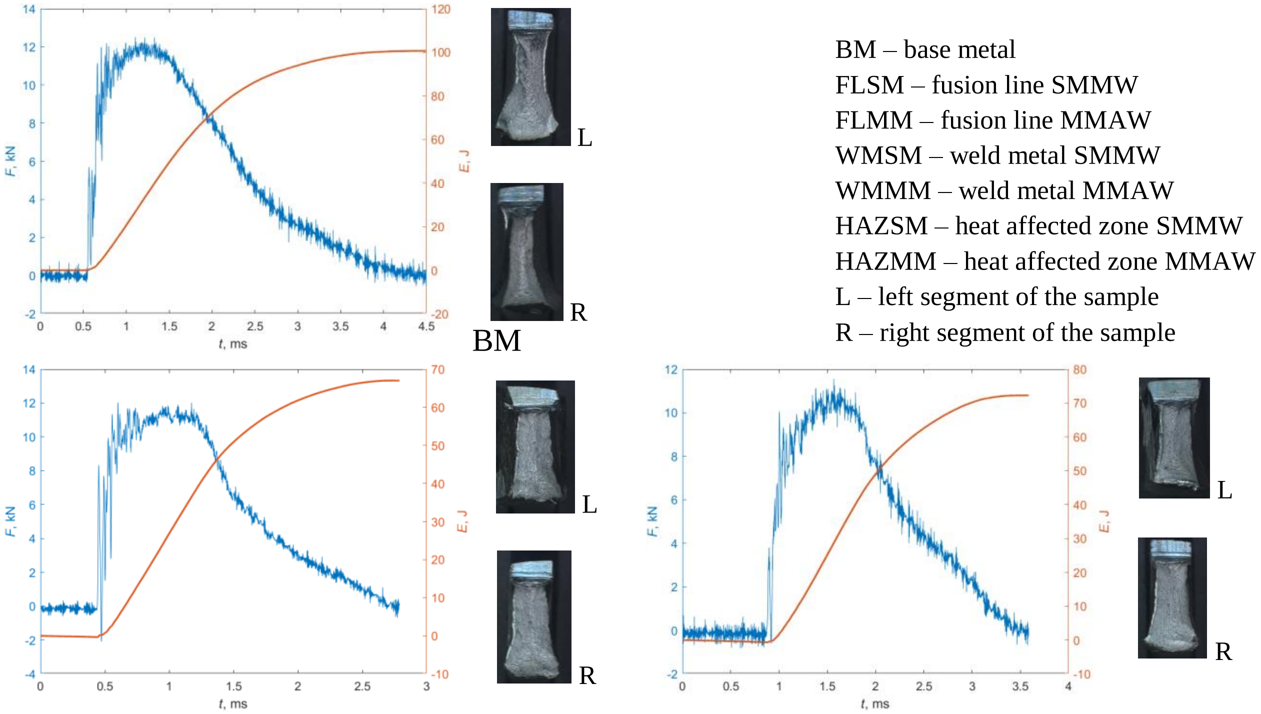


Figure 4. The appearance of the welded joint (face and root)

4. Results analysis

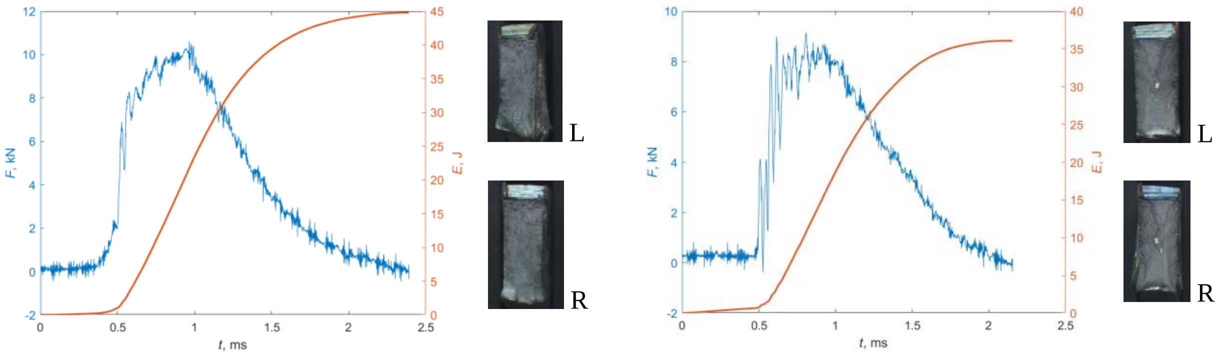
Determination of Charpy impact toughness was performed according to the EN ISO148-1 standard [8] using a "V" notch. Thanks to the instrumented Charpy pendulum, we are able to decompose the total energy (E_u) into the initiation energy (E_i) and the propagation energy (E_p) of the crack. The results of testing the samples show that the greater part of the energy spent on the fracture of the test sample is related to the phase of crack propagation. It is a sign of good resistance to brittle fracture because $E_p > E_i$. The material or the welded joint has pronounced ductility. We can draw the same conclusion by analyzing the force-time (F-t) and energy-time (E-t) failure curves (Figure 5).



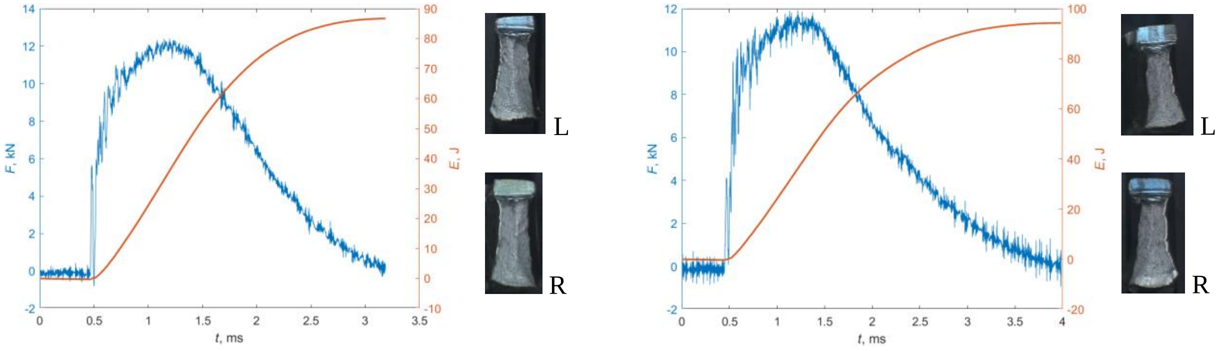
BM – base metal
FLSM – fusion line SMMW
FLMM – fusion line MMAW
WMSM – weld metal SMMW
WMMM – weld metal MMAW
HAZSM – heat affected zone SMMW
HAZMM – heat affected zone MMAW
L – left segment of the sample
R – right segment of the sample

FLSM FLMM

Figure 5. The results of instrumented Charpy impact test



WMSM WMMM



HAZSM HAZMM

Figure 5. The results of instrumented Charpy impact test (continuation)

The ratio of E_u, E_i i E_p values by zones of welded joint made by SMAW and MMAW procedure is shown in Figure 6 and Figure 7, respectively.

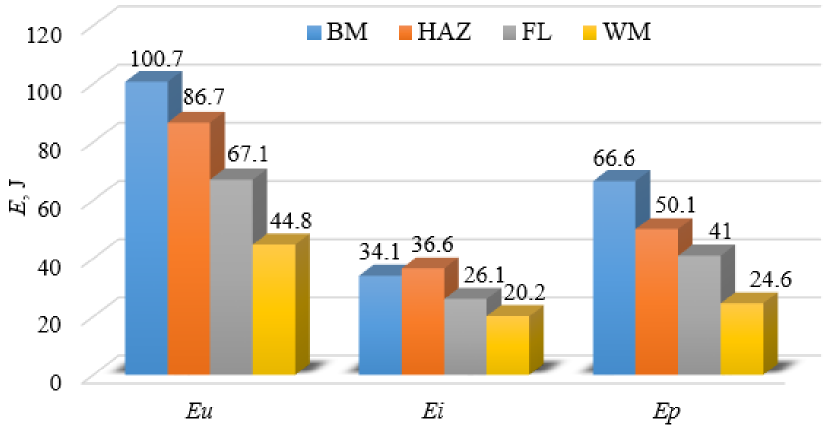


Figure 6. Values of E_u, E_i, E_p by zones for welded joints made by the SMAW process

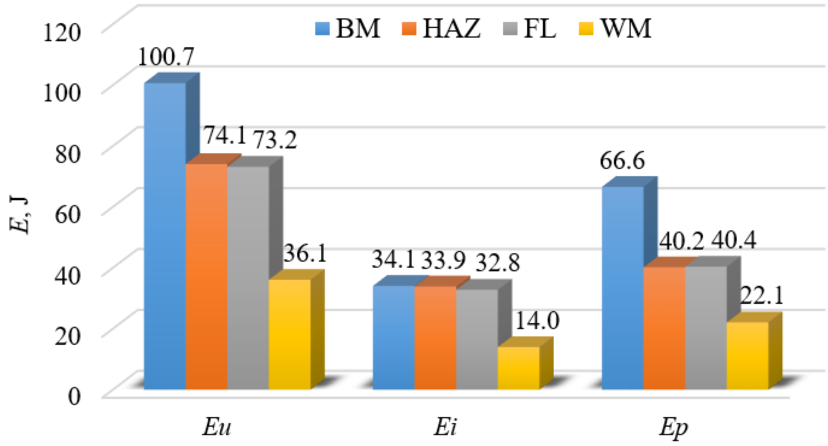


Figure 7. Values of E_u, E_i, E_p by zones for welded joints made by the MMAW process

The ratio of E_p/E_i (Figure 8) of welded joints in ductile welded joints is more pronounced. The diagram (Figure 9) shows a comparative overview of impact toughness values (K_v, J/cm^2) by zone of welded joints. Base metal has a dominantly higher impact toughness and it amounts to 314.69 J/cm^2. In the HAZ of the welded joint obtained by the SMAW welding process, the impact toughness is higher by 17% compared to the welded joint obtained by MMAW. Also, in the WM zone, SMAW samples have a higher impact toughness value, by 24.2%. In the FL zone, the test samples produced by the MMAW process have a higher impact toughness by 9.2%.

Figure 10 shows the values of the maximum force (F_m), which is defined as the maximum force value on the *F*- *t* curve with a "V" notch in different zones of the welded joint. From the diagram, it can be seen that the maximum force values occur with welded joints realized by the SMAW process.

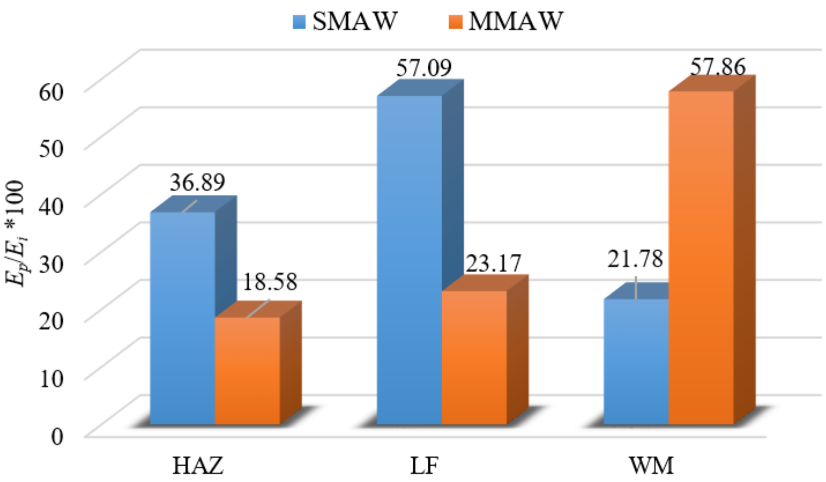


Figure 8. E_p/E_i ratio by zones of welded joints realized by SMAW and MMAW

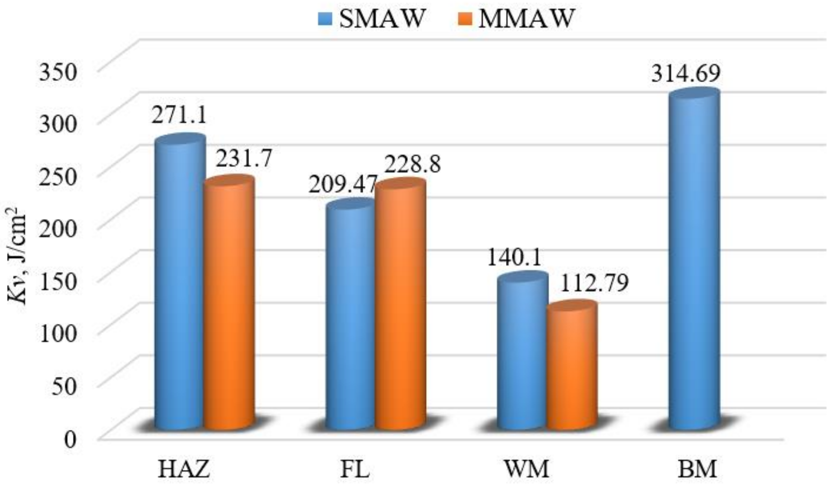


Figure 9. Impact toughness - a comparative review of equivalent zones

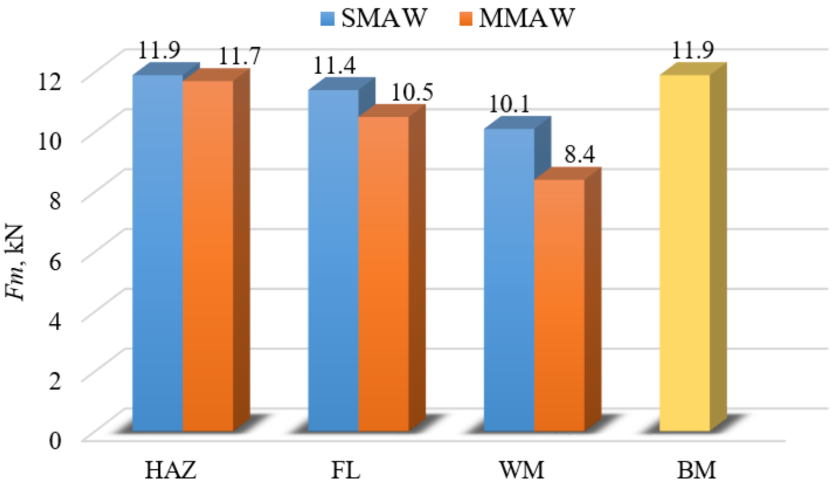


Figure 10. The value of maximum F_m force

5. Conclusions

The results obtained by testing the impact toughness using the Charpy method show that the welded joint obtained by the SMAW welding process has greater ductility, which makes it more reliable. The results of the fracture energy of the test sample are analogous to the results of the force required to break them. The E_p/E_i ratio in the WM and HAZ zones is more favorable in the case of welded joints realized by the SMAW process. The test results obtained are indicators and recommendations for the justification of the application of the SMAW tolerance for duplex steel welding. The adventage of application over MMAW is especially pronounced when it is necessary and possible to automate the process.

6. References

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