

# Studies on welding parameters and prediction of imperfections and mechanical properties in the GMAW process

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## 1. Introduction

Welding is an essential manufacturing process performed in almost every major industry. The weld quality and integrity are critical to safety for an extensive range of products and structures. GMAW is one of the most commonly used arc welding process and is continuously improved by selecting the best combination of welding materials, welding technologies and welding parameters to produce a welded structure with the required properties. In GMAW, as in any welding process, the welding parameters play an important role in product quality as it affects the mechanical properties, structural characteristics and geometry of welded joints [1-6].

Selecting the optimal welding parameters to meet the required specifications is complicated as the welding quality can be affected by several variables such as the chemical composition of the parent / base materials and heat treatment, wire and protective gas used [3, 7].

On the other hand, experimental optimization of the process is time consuming and costly [5, 6, 8]. To overcome this problem several methods and approaches have been used, such as design of experiments and statistical techniques [3-5, 8, 9].

Among the various widely used methods, in the current studies the factorial experimental design method was used to identify the significant process parameters and to obtain correlations between the welding parameters and output indicators related to the quality of joints, as this method is useful for modelling and analyzing of issues involving multiple parameters.

## 2. Experimental work

### 2.1 Material and methods

For the experimental work, S235JR+AR structural steel plates of 2 mm, 4 mm and 8 mm thickness, according to SR EN 10025-2 were used as base material. The chemical composition of the base material is presented in table 1 and the main mechanical characteristics are presented in the table 2.

Table 1. Chemical composition of the base material, S235JR+AR structural steel.

C [%]	Mn [%]	P [%]	S [%]	N [%]	Cu [%]
0.19	1.50	45	45	14	0.60

Table 2. Mechanical characteristics of the base material, S235JR+AR structural steel.

Yield strength Rp <sub>0.2</sub> [N/mm <sup>2</sup> ]	Tensile strength R <sub>m</sub> [N/mm <sup>2</sup> ]	Elongation at break A <sub>s</sub> [%]	Impact energy KV <sub>(+20°C)</sub> [J]
235	360 - 510	26	27

To realize the weld, 1.0 mm diameter 3Si1 welding wire (according to SR EN ISO 14341, commercial naming BÖHLER SG2), was used. The chemical composition of the welding wire is presented in table 3 and the associated main mechanical characteristics are presented in table 4.

Table 3. Chemical composition of welding wire, 3Si1.

C [%]	Si [%]	Mn [%]	P [%]	S [%]	Ni [%]
0.06 - 0.14	1.00 - 1.30	1.30 - 1.60	0.025	0.025	0.015
Cr [%]	Mo [%]	V [%]	Cu [%]	Al [%]	Ti + Zr [%]
0.15	0.15	0.03	0.35	0.02	0.15

Table 4. Mechanical characteristics of the welding wire, 3Si1.

Yield strength Rp <sub>0.2</sub> [N/mm <sup>2</sup> ]	Tensile strength R <sub>m</sub> [N/mm <sup>2</sup> ]	Elongation at break A <sub>s</sub> [%]	Impact energy KV <sub>(+20°C)</sub> [J]
420	500 - 640	20	27

M2.1 protection gas, (according to SR EN ISO 14175, commercial naming CORGON18) was used in the welding process. The main characteristics are presented in table 5.

Table 5. Characteristics of the welding gas, M2.1(CORGON 18).

CO <sub>2</sub> [%]	Ar [%]	Volume [L]	Pressure [bar]	Content weight [kg]
15 - 25	Rest	15	200	3.88

GMAW process was used to obtain butt welded sample of sheets. To avoid human error robot system (consisting of robotic arm and integrated welding source) was used to implement the experimental welding program.

In order to study the influence of the welding parameters on quality of obtained welds (size and number of imperfections) as well as to predict the mechanical characteristics of those, factorial experiments were designed for each base material thickness, taking into account the main process parameters: welding current  $I_a$  [A], welding voltage  $U_a$  [V], travel speed  $v$  [cm/min] and electrode's free length,  $l$  [mm]. Thus, the factorial experiments envisaged the study of four influence factors on two levels and included three replicas at the central point, according to table 6.

Preliminary tests were made to estimate the range of the welding parameters, so that the process is stable. The parameters range obtained varied on the thickness of the sheets and the geometry of the welding seam.

Table 6. Factorial model of welding variants.

Test no.	Welding current $I_a$ [A]	Welding voltage $U_a$ [V]	Welding speed $v$ [cm/min]	Free length $l$ [mm]
1	-1	1	-1	1
2	-1	-1	-1	1
3	-1	1	-1	-1
4	1	-1	1	1
5	-1	-1	1	-1
6	1	1	-1	-1
7	1	-1	-1	1
8	1	-1	1	-1
9	1	1	1	1
10	-1	1	1	1
11	-1	-1	1	1
12	1	1	1	-1
13	1	1	-1	1
14	1	-1	-1	-1
15	-1	-1	-1	-1
16	-1	1	1	-1
17	0	0	0	0
18	0	0	0	0
19	0	0	0	0

where: “1” represented the upper value, “0” represented the center point value and “-1” represented the lower value of the studied process parameters.

Based on the preliminary experimental work, the upper, center point and lower value of the parameters used in the factorial experiments, depending of the thickness of the plates, are presented in table 7 to 9.

Table 7. Welding parameters used for 2 mm plate thickness.

Value	$I_a$ [A]	$U_a$ [V]	$v$ [cm/min]	$l$ [mm]
Upper	140	20	75	12
Center point	125	19	65	10
Lower	110	18	55	8

Table 8. Welding parameters used for 4 mm plate thickness.

Value	$I_a$ [A]	$U_a$ [V]	$v$ [cm/min]	$l$ [mm]
Upper	155	22.5	30	12
Center point	135	21	25	10
Lower	115	19.5	20	8

Table 9. Welding parameters used for 8 mm plate thickness.

Value	$I_a$ [A]	$U_a$ [V]	$v$ [cm/min]	$l$ [mm]
Upper	275	29	70	12
Center point	250	27	60	10
Lower	225	25	50	8

## 2.1. Experimental testing program

In order to evaluate the quality of the welded joints, a testing program consisting of nondestructive tests, mechanical tests and analyses was designed and implemented. Thus, all welded samples were 100% examined using the magnetic-particle testing (MT) method to identify surface defects as well penetrant testing method (PT) using X-ray to highlight internal welding defects.

Additionally, 8 mm thick welded samples were complementary examined using ultrasonic testing (UT) method (applied also for internal defects). Further, samples for macroscopic analyses and mechanical tests (tensile tests, bending tests, Vickers hardness tests) were sampled from the welded plates and tested, according to EN ISO 15614-1: 2017.

## 3. Results and discussion

In order to determine the correlations between the welding parameters and the mechanical characteristics of the welded joints, specialized software for regression analysis was used. In the following the summary of results obtained for but welded joints of plates made of S235 structural steel of 2 mm, 4 mm and 8 mm thickness is presented.

Thus, in the case of 2 mm butt welded joints, correlations between the welding process parameters and the tensile strength ( $R_m$ ) of the joint are shown in figures 1.

The correlation is described by the following equation (1):

$$R_m = -496.2 - 57.810 \cdot I_a + 191.115 \cdot U_a + 63.40 \cdot v + \\ + 99.32 \cdot l + 1.59583 \cdot I_a \cdot U_a + 0.43458 \cdot I_a \cdot v + 0.00208 \cdot I_a \cdot l - \\ - 5.8188 \cdot U_a \cdot v - 2.4063 \cdot U_a \cdot l - 0.4906 \cdot v \cdot l \quad (1)$$

Figure 2 presents the influence of welding parameters on the number of imperfections in case of butt welded joint of 2 mm thick plates.

The correlation is described by the following equation (2):

$$\text{The number of imperfections} = -24.3 + 0.308 \cdot I_a + \\ + 0.42 \cdot U_a + 0.20 \cdot v - 0.79 \cdot l - 0.00833 \cdot I_a \cdot U_a - 0.00167 \cdot I_a \cdot v - \\ - 0.00417 \cdot I_a \cdot l + 0.0625 \cdot U_a \cdot l \quad (2)$$

Figure 3 presents the influence of welding parameters on the maximum size of imperfections, in case of butt welded joint of 2 mm thick plates.

The correlation is described by the following equation (3):

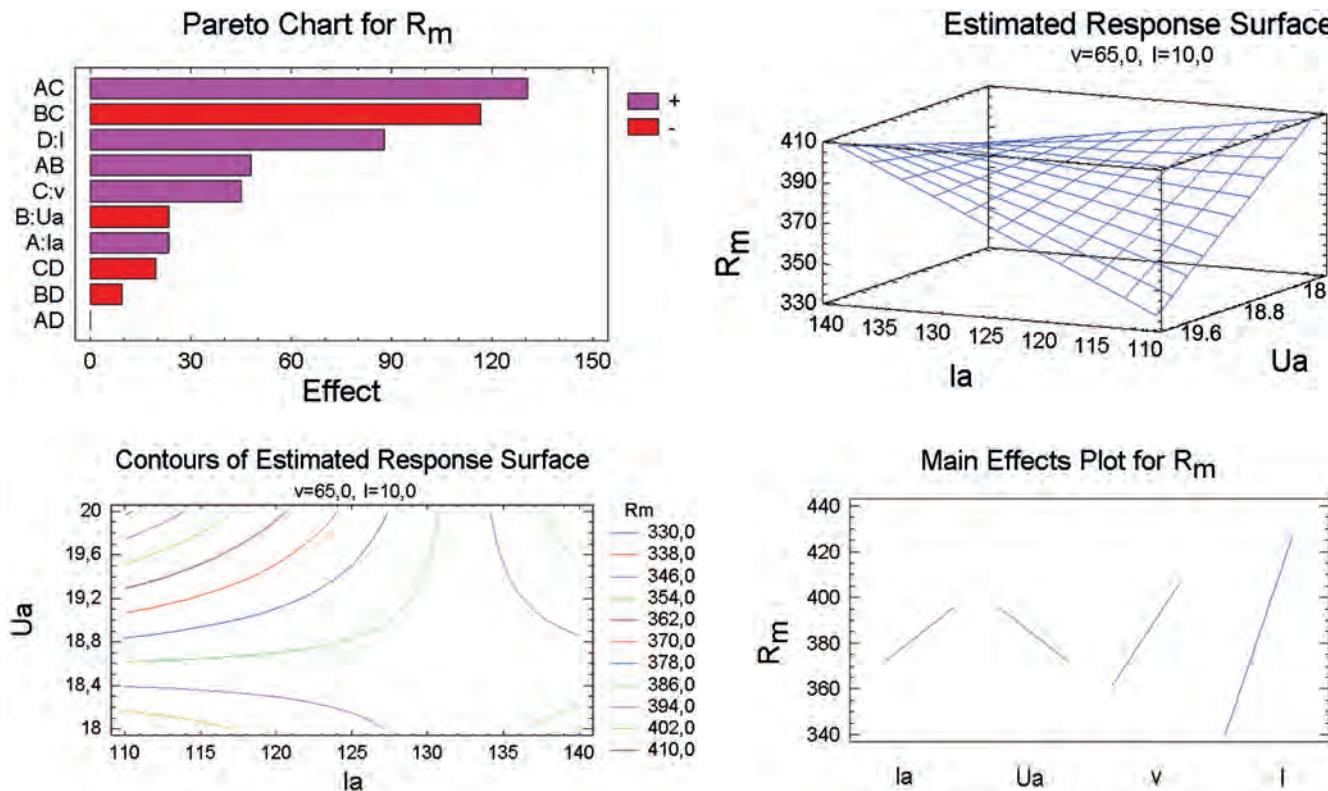


Figure 1. The correlations between the parameters of the welding process and the tensile strength (2 mm thick butt-welded plates).

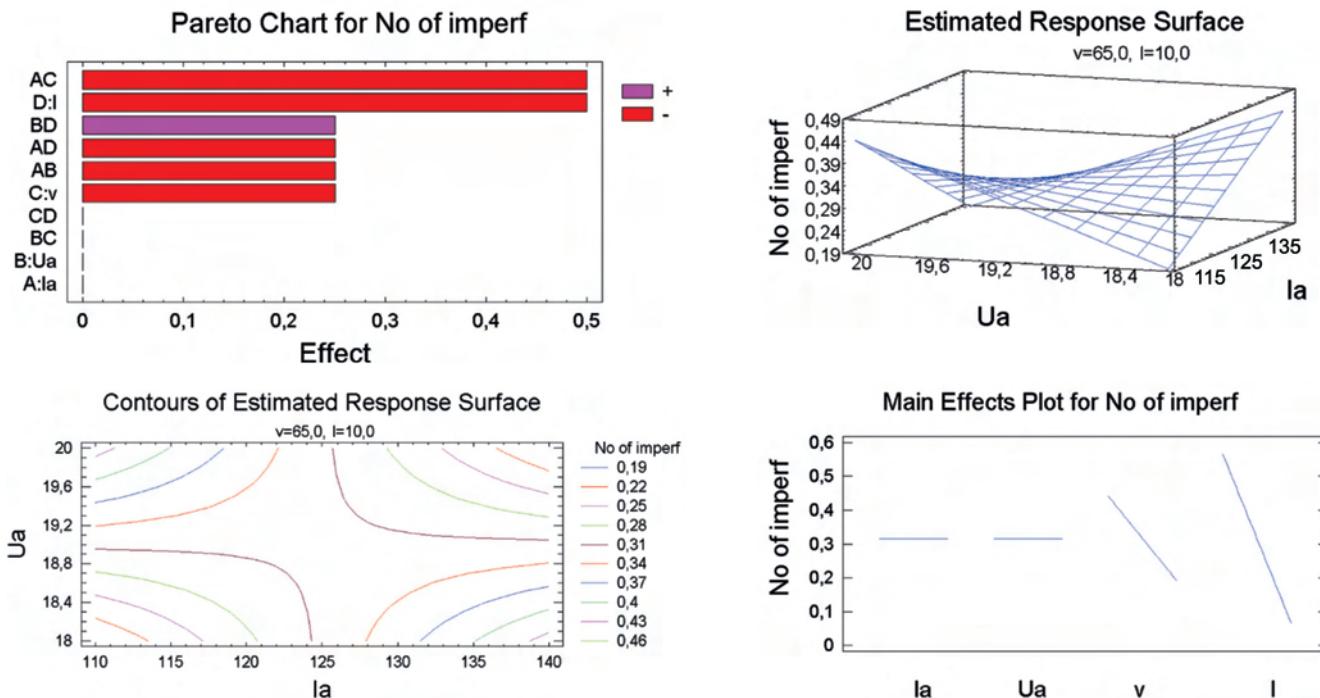


Figure 2. The correlations between the parameters of the welding process and the number of imperfections (2 mm thick butt-welded plates).

The maximum dimension of imperfection = -14.9 -  
 $-0.106 \cdot I_a - 2.42 \cdot U_a + 0.96 \cdot v + 4.02 \cdot l + 0.02033 \cdot I_a \cdot U_a -$   
 $-0.00305 \cdot I_a \cdot v - 0.00125 \cdot I_a \cdot l - 0.0039 \cdot U_a \cdot v - 0.0406 \cdot U_a \cdot l -$   
 $-0.0496 \cdot v \cdot l$

In a similar way were found correlations for butt welded joints of 4 mm as following:

- equation (4) for the influence of the welding process parameters on tensile strength ( $R_m$ );

$$\begin{aligned}
 R_m = & 1168.4 + 4.295 \cdot I_a - 7.52 \cdot U_a + 10.22 \cdot v - \\
 & 255.29 \cdot l - 0.13399 \cdot I_a \cdot U_a + 0.04182 \cdot I_a \cdot v - \\
 & 0.06108 \cdot I_a \cdot l - 2.2026 \cdot U_a \cdot v + 8.9517 \cdot U_a \cdot l + \\
 & + 2.9307 \cdot v \cdot l
 \end{aligned} \quad (4)$$

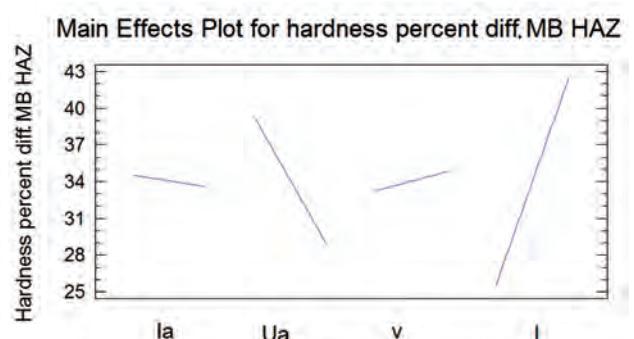
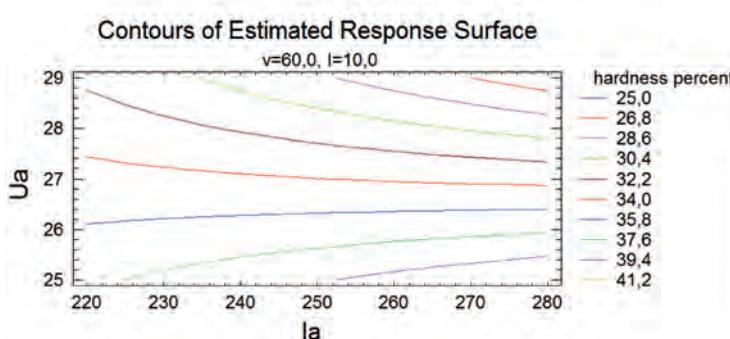
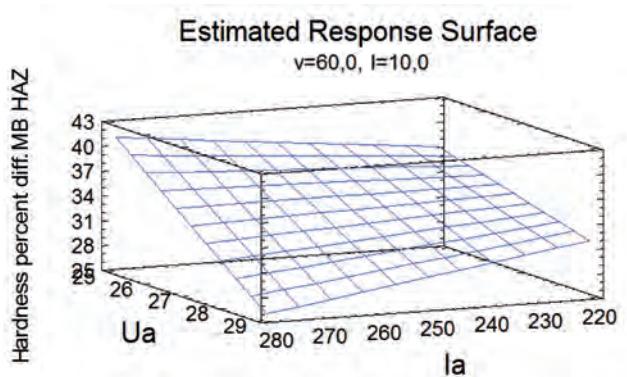
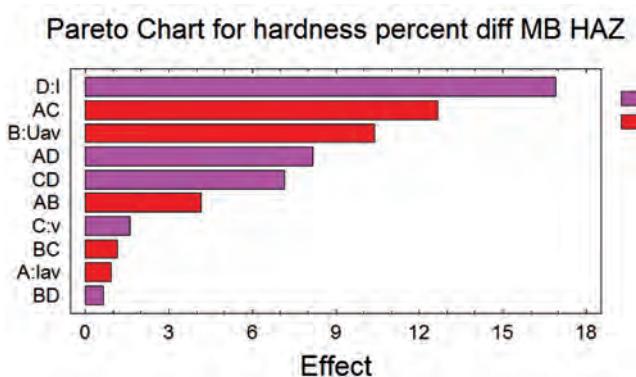
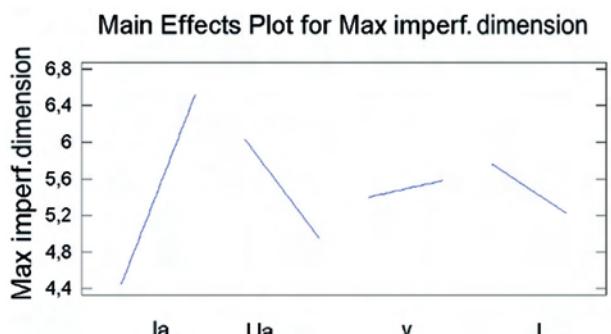
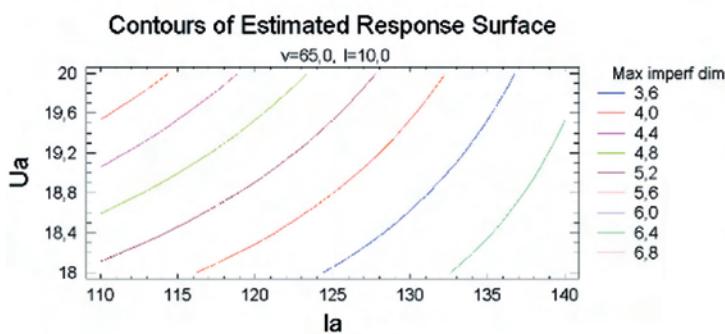
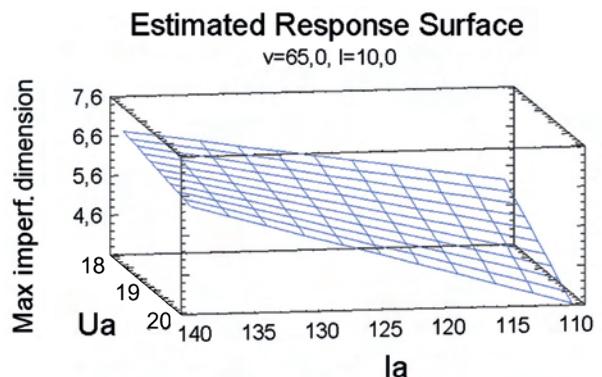
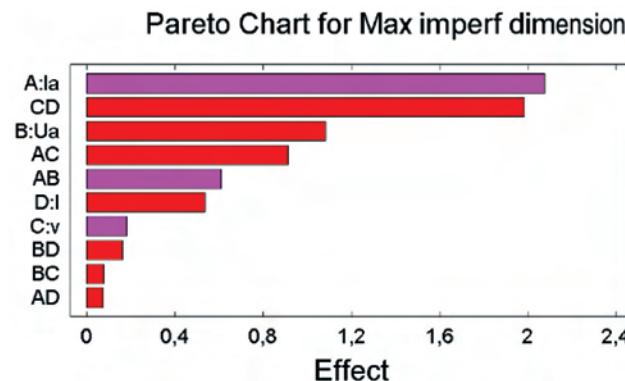


Figure 3. The correlations between the parameters of the welding process and the maximum size of imperfections (2 mm thick butt-welded plates).

- equation (5) for the influence of the welding process parameters on the number of imperfections;

$$\begin{aligned} \text{No. of imperfection} = & 6.0 - 0.057 \cdot I_a + 0.13 \cdot U_a - \\ & - 0.13 \cdot v + 0.07 \cdot l + 0.00057 \cdot I_a \cdot U_a - 0.00009 \cdot I_a \cdot v + \\ & + 0.00291 \cdot I_a \cdot l + 0.0023 \cdot U_a \cdot v - 0.0359 \cdot U_a \cdot l + \\ & + 0.0116 \cdot v \cdot l \end{aligned} \quad (5)$$

- equation (6) for the influence of the welding process parameters on maximum size of imperfections;

Max. dimension of imperfection = 149.5 -

$$\begin{aligned} & - 1.437 \cdot I_a + 3.38 \cdot U_a - 3.17 \cdot v + 1.82 \cdot l + 0.01387 \cdot I_a \cdot U_a - \\ & - 0.00195 \cdot I_a \cdot v + 0.07352 \cdot I_a \cdot l + 0.056 \cdot U_a \cdot v - \\ & - 0.9029 \cdot U_a \cdot l + 0.293 \cdot v \cdot l \end{aligned} \quad (6)$$

In a similar way were found correlations for butt welded joints of 8 mm as following:

- equation (7) for the influence of the welding process parameters on tensile strength ( $R_m$ );

$$\begin{aligned} R_m = 371.6 + 2.938 \cdot I_a + 3.1 \cdot U_a - 11.1 \cdot v - 4.93 \cdot l - \\ - 0.08288 \cdot I_a \cdot U_a + 0.01877 \cdot I_a \cdot v - 0.16387 \cdot I_a \cdot l + \\ + 0.099 \cdot U_a \cdot v + 0.9423 \cdot U_a \cdot l + 0.3716 \cdot v \cdot l \end{aligned} \quad (7)$$

- equation (8) for the influence of the welding process parameters on the number of imperfections;

$$\begin{aligned} \text{No. of imperfection} = -4.1 + 0.07 \cdot I_a - 0.01 \cdot U_a - \\ - 0.04 \cdot v - 0.57 \cdot l - 0.00148 \cdot I_a \cdot U_a - 0.00034 \cdot I_a \cdot v - \\ - 0.00082 \cdot I_a \cdot l + 0.0026 \cdot U_a \cdot v + 0.0185 \cdot U_a \cdot l + 0.0042 \cdot v \cdot l \end{aligned} \quad (8)$$

- equation (9) for the influence of the welding process parameters on maximum size of imperfections;

$$\begin{aligned} \text{Max. dimension of imperfection} = -103.1 + 1.761 \cdot I_a - \\ - 0.13 \cdot U_a - 0.89 \cdot v - 14.24 \cdot l - 0.03723 \cdot I_a \cdot U_a - 0.00844 \cdot I_a \cdot v - \\ - 0.02073 \cdot I_a \cdot l + 0.0643 \cdot U_a \cdot v + 0.4654 \cdot U_a \cdot l + 0.1056 \cdot v \cdot l \end{aligned} \quad (9)$$

For 8 mm thick butt-welded joints, the influence of the welding parameters on the Vickers hardness (HV) differences between the base material (BM) and heat-affected zone (HAZ) of welds were assessed. Obtained results are presented in figure 4.

The correlation is described by the following equation (10):

$$\begin{aligned} \text{HV hardness differences BM-HAZ} = -311.2 + \\ + 1.805 \cdot I_a + 8.68 \cdot U_a + 5.40 \cdot v - 29.13 \cdot l - \\ - 0.04148 \cdot I_a \cdot U_a - 0.02533 \cdot I_a \cdot v + 0.08168 \cdot I_a \cdot l - \\ - 0.0287 \cdot U_a \cdot v + 0.081 \cdot U_a \cdot l + 0.1792 \cdot v \cdot l \end{aligned} \quad (10)$$

The analysis of the obtained results, shows that the tensile strength of the welded joints increased with the increase of the electrode wire feed rate (which lead to an increase in welding current) and decreased with the increase of the welding voltage.

When the welding voltage increase, the width of the weld seam increase, and thus linear energy is distributed over a larger surface. Under these conditions, in conjunction with the other welding parameters, the linear energy may be insufficient to produce a suitable weld with a required tensile strength.

On the other hand, the joint tensile strength increases as the welding speed increases. This can be explained as follows: increasing in welding current leads in increasing of the deposition rate, and thus, a higher welding speed is required to obtain a proper weld.

The experiments show that, in case of butt-welding thin plates, for the welding parameters range selected, the number of imperfections in the welded joint increase with decreasing in welding speed and with decreasing of free length (nozzle-workpiece distance). On the other hand, the maximum size of detected defects increases with increasing of the welding current as well as in case of welding voltage decreases.

In the case of 8 mm butt-welded plates, the welding voltage and the free length have major influence on the hardness difference between HAZ and BM. Thus, with increasing in welding voltage and decreasing of the free length, the hardness difference between HAZ and BM is reducing.

## 4. Conclusions

A factorial experiment was performed on butt welded plates of structural steel using the GMAW process. The study was focused on the effect of the welding parameters on the tensile strength of the butt welded joint, to select the optimal welding parameters to obtain maximum mechanical characteristics of the weld.

The influence of each welding parameters on mechanical characteristics of the weld were experimental determined. The process parameters that had the greatest impact on the tensile

strength of the welded joint were the welding current, the welding voltage, the welding speed and the free length.

Based on the results obtained, regression models for different thicknesses of base materials were developed. Determined regression models can be used to estimate the number and the maximal dimension of imperfections and to select parameters of the GMAW process for joining of structural steel plates S235, to obtain required tensile strength of the weld, which is exploited under different loading condition.

The models obtained could be used for all steel from group 1 according to ISO/TR 15608:2017, with specified minimum yield strength of  $R_{eH} \leq 275 \text{ N/mm}^2$ , to obtain proper Welding Procedure Specification (WPS), to meet the quality level of imperfections, required for various applications.

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