Statistical correlations between welding parameters and quality indicators for 8 mm thick T-joints structural steel realized with GMAW process

A.V. Bîrdeanu, A.C. Murariu

National R&D Institute for Welding and Material Testing – ISIM Timisoara, Romania

E-mail: research@isim.ro

Keywords

GMAW, structural steel, factorial design, data processing, welding parameters, mechanical properties, NDT, destructive test, T-joints

1. Introduction

Joining is recognized as one of the "key enabling technologies" at the European and global level due to its transversal interaction with almost all industrial domains to which it adds value [1, 2]. Due to this fact, the joining / welding process can be critical for a high number of industrial processes and hence its requirements in respect to quality and reproducibility. Consequently, the designers and customers' quality and price requirements become more restrictive on the global market. This in turn, implies that the designers and welding engineers need tools for helping them in deciding which welding technologies are necessary to be used in order to increase the added value of the products.

While some of these tools that are available on the market [3-6] are mainly focused on either storing or documenting the welding process / welding personnel and can be exploited for easier selection of process parameters for the next projects, others are focused on providing means of generating welding procedure specifications based on specific algorithms based on international standard and ensuring traceability, or provide means of welding structures cost calculations, not much of them incorporate a "smart" system for helping the designers and welding engineers adjust the process parameters to optimize the manufacturing processes. These "smart" systems can exploit the previously available information as input if the proper required information is available but also can require generating of input data and models that can be included in the system, i.e. into a knowledge-based system. Such a system was designed and realized in the framework of the KBSWeld international project [7].

The current paper presents the work carried out for generating input data for such a knowledge-based system and the results that can be either integrated into such system or used independently for welding process optimization, when realizing T-joints by using structural steel.

2. Material and methods

For the experimental work the same setup in [8] was used and the base material (BM) was S235JR+AR (according to SR EN 10025-2), 8 mm in thickness, welded with GMAW process in PB position, using 1.0 mm diameter filler metal 3Si1 welding wire (according to SR EN ISO 14341) and M2.1 protection gas, (according to SR EN ISO 14175, commercial naming CORGON18) with a Q = 15 l/min flow was used for the welding protection. To ensure a high degree of repeatability a robotic system was used during the whole process.

The joint geometry for welding the two types of BM is presented in figure 1.

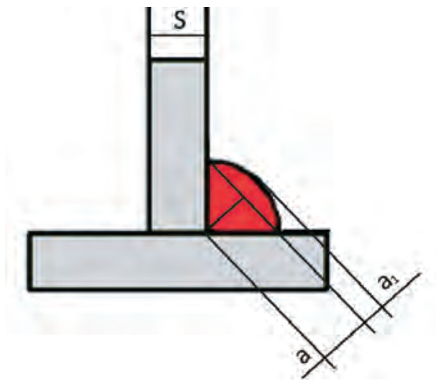


Figure 1. The T-joint geometry,
S=8 mm, a=5.4 mm, a_1=0.3 mm.

For generating the envisaged IO-s as feed for the knowledge based system, a full factorial full factorial experiment with four influence factors (IF) and three replicas in the central point was designed for the welding trials as presented in table 1 for studying the influence of welding current – Ia, welding voltage – Ua, welding speed – vs, free length of the electrode wire – l onto the welding quality indicators. Preliminary welding trials were also done in order to establish the central point (CP) of the trials and the experimental domain that is stable enough based on minimum inspection of the welding process results, e.g. visual test [9] and the aspect of the weld. Following the preliminary welding trials, the IF variation presented in table 2 was established.

For determining the quality indicators, the welded samples were subjected, based on a testing plan, to non-destructive tests (NDT), e.g. visual test (VT) and magnetic-particle test (MT) [10] to identify surface imperfections and, to highlight internal welding imperfections and destructive testing respectively, i.e. mechanical testing (technological fracture test [11]) and metallographic analysis (macroscopic test [12] and hardness measurements [13]), according to the sampling plan presented in figure 2, based on the existing standard [14].

Table 1. Full factorial experiment 2^4+3 CP – encoded values of the experimental trial.

No.	Ia [A]	Ua [V]	v [cm/min]	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

Table 2. Influence factors applied for the factorial design welding trials, S235JR+AR, 8 mm thick, T-joint, single pass.

IF / Real Value	Ia [A]	Ua [V]	vs [cm/min]	l [mm]
High	248	28.6	38.5	12
Central Point	225	26.0	31.5	10
Low	202	23.4	35.0	8

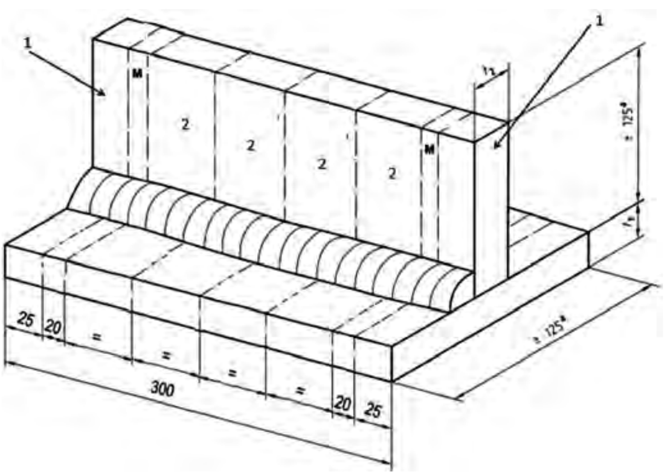


Figure 2. Sampling plan for the realized GMAW T joints [9]. 1 - Parts that are to be removed; 2 - Technological fracture test samples; M - Area for macroscopic analysis and hardness tests specimens

3. Results and discussion

Following the experimental testing program, it was able to underline some of the main imperfections that occurred due to the process parameters combinations. For example, one can notice from tables 3 and 4 which presents the map of the identified imperfections following the macroscopic test and NDT respectively, which imperfections occurred more and to what extent based on the process parameters combinations. This data was of value for the KBSWeld system for training the logic of the system but also it can be used by the welding engineers looking to improve / optimize their welding procedures.

Table 3. Macroscopic tests results map (according to [12] and [15]).

Trial	402	512	2017	5012	5214	max. dim.	no. imperf.
1				TRUE		0.8	1
2							
3		TRUE				1,5	1
4	TRUE				TRUE	3,4	2
5							
6							
7							
8	TRUE					1,5	1
9	TRUE		TRUE			6,5	2
10	TRUE			TRUE		3,6	2
11							
12				TRUE		0.9	1
13							
14				TRUE		0.6	1
15							
16	TRUE			TRUE		4,45	2
17							
18							
19							

Table 4. Excerpt of the NDT testing results (most common imperfections that were noticed) – according to [15]).

Trial	5011	5012	500	503	505	506
1	0.6	0.5		0.9	70	
2				0.7	80	
3				1,4	115	
4			TRUE	1,4	50	2,5
5				1	110	
6				2.4	130	
7			TRUE	1.8	100	
8		0.3	TRUE	1.9	100	2
9				1.8	90	
10		0.3		0.9	80	
11				1.8	95	
12		0.2		1.1	90	
13				2.9	120	
14		0.2		1.1	80	1,5
15				1.5	80	0.7
16		0.4	TRUE	1	60	
17				2.6	90	
18				2	100	
19	0.1	0.1		2.6	110	

An important result of the experimental work was obtained after the hardness measurements onto the macroscopic samples as presented in figures 3 and 4. When improper combination of the welding parameters was selected and used, lack of penetration / partial penetration (figure 3) as well as continuous or intermittent undercut (figure 4) were highlighted on macroscopic samples extracted from the T-welded joints.

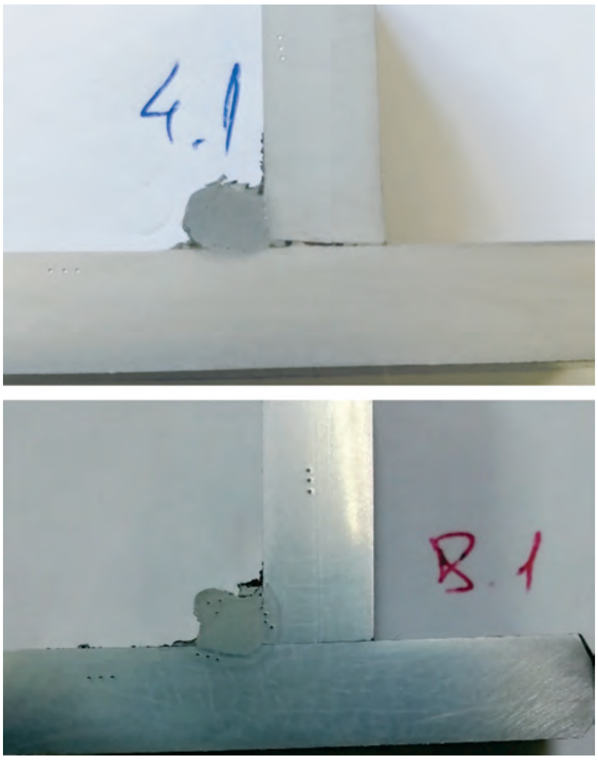


Figure 3. The aspects of macroscopic samples with lack of penetration imperfections type.

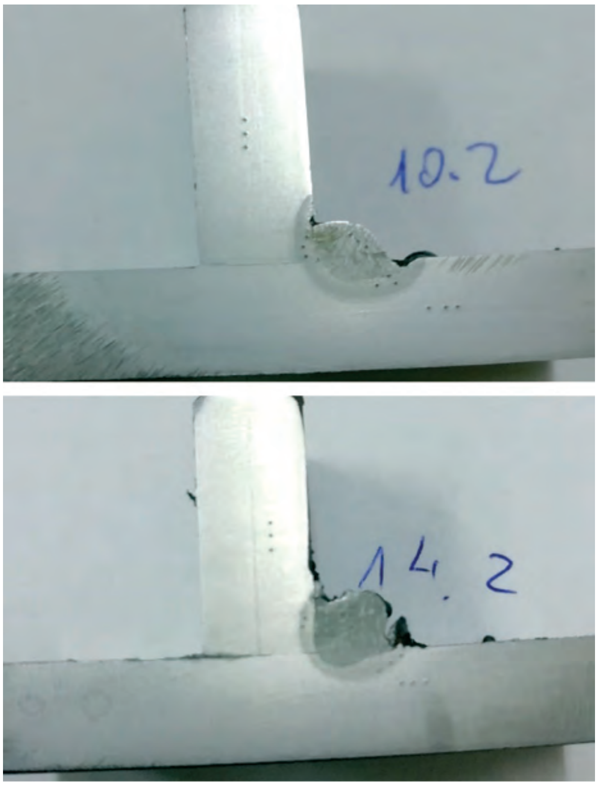


Figure 4. The aspects of macroscopic samples with undercut imperfections type.

In some cases, excessive convexity and incorrect weld toe was also evinced (figures 4 and 5).

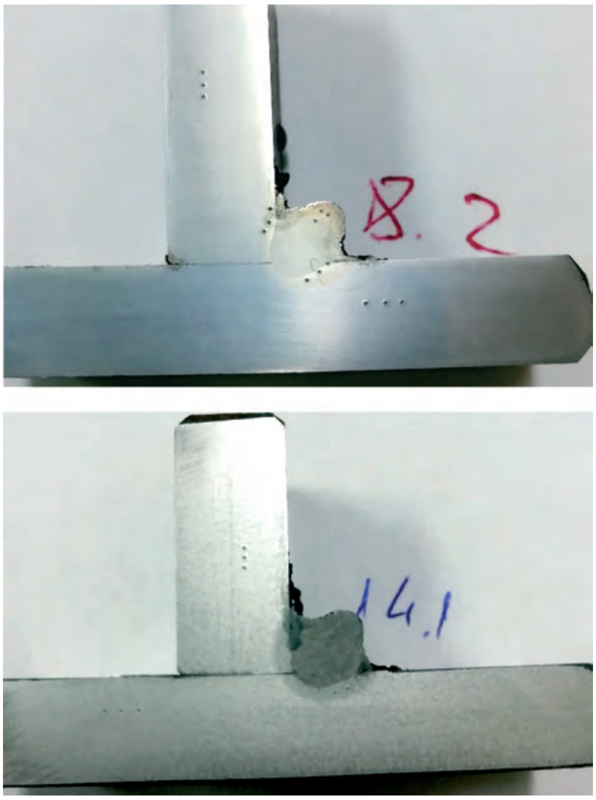


Figure 5. The aspects of macroscopic samples with incorrect weld toe.

If the welding parameters was proper selected, the welded joint has acceptable defects with appropriate structural and mechanical characteristics (figure 6).

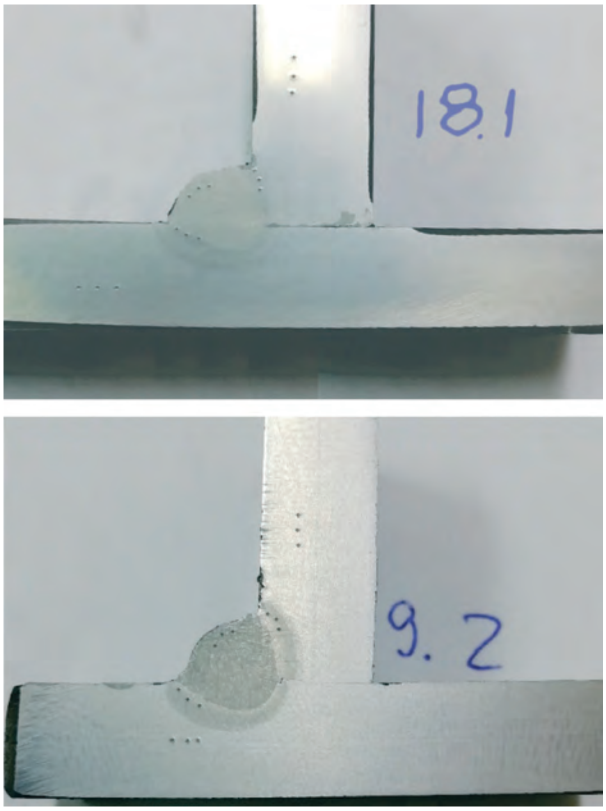
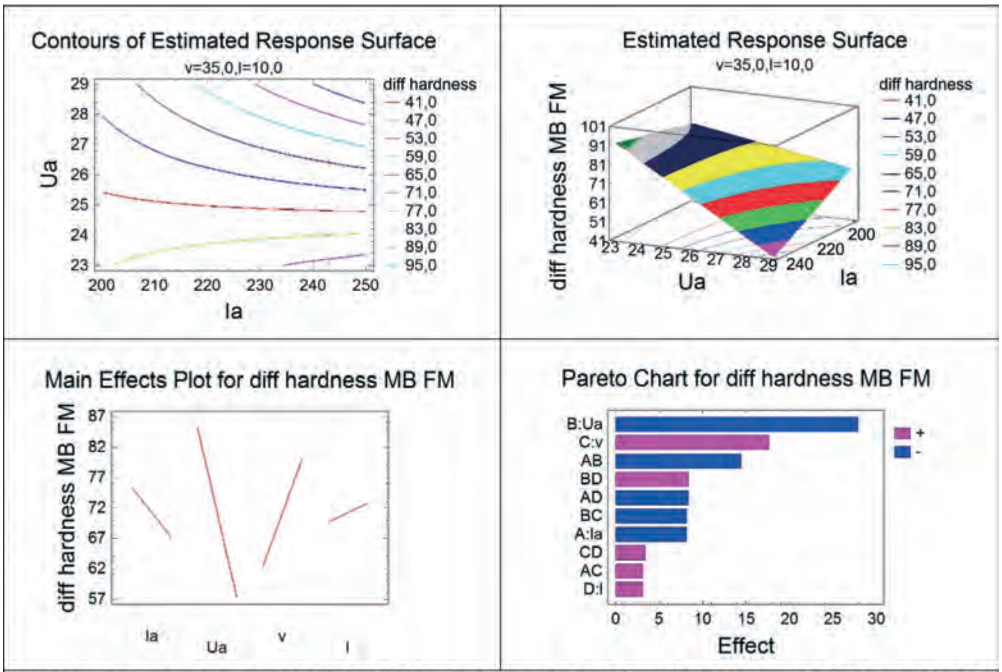


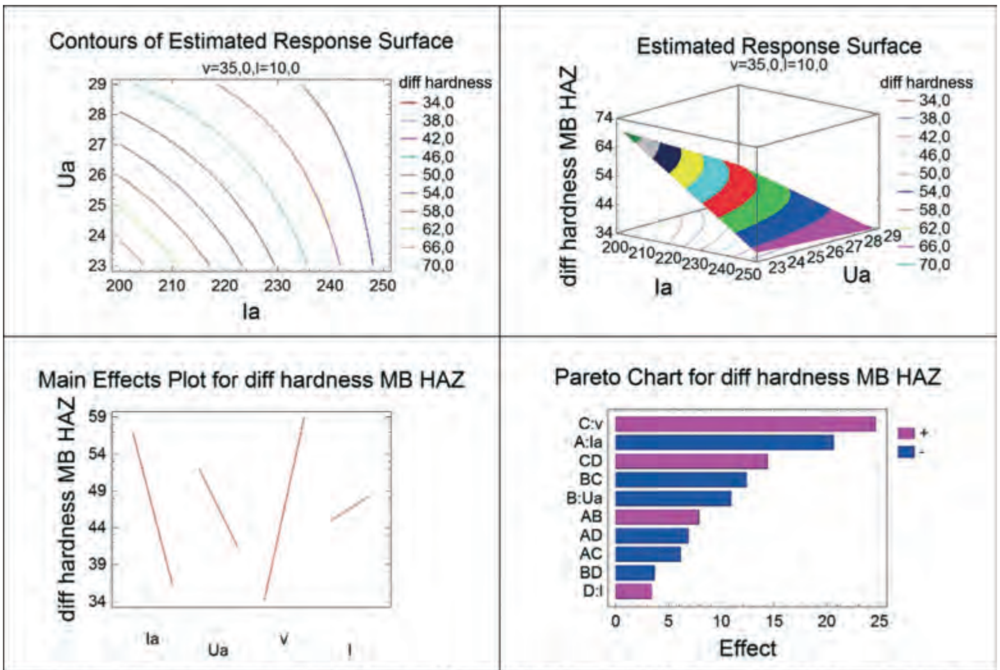
Figure 6. The aspects of proper welded macroscopic samples.

The values obtained from the hardness measurements were processed in order to determine statistical correlations between the welding parameters variation and two important objective functions (OF), i.e. Vickers hardness (HV) differences between the base material (BM) and Weld (FM) (I) and Vickers hardness (HV) differences between the base material (BM) and heat-affected zone (HAZ) (II), by using specialized software for such an analysis. The obtained results are presented in figures 7 and 8, while the correlations are described in equations below the above-mentioned figures.



Hardness difference between the BM and FM = -713,205 + 3,17935*Ia + 29,2548*Ua + 7,34705*v - 8,11141*l - 0,120192*Ia*Ua + 0,0194099*Ia*v - 0,0910326*Ia*l - 0,446429*Ua*v + 0,805288*Ua*l + 0,241071*v*l

Figure 7. Hardness values difference between the base material (BM) and weld zone (FM).



Hardness difference between the BM and HAZ = -362,214 - 0,0815217*Ia + 10,3773*Ua +19,4884*v - 9,21739*l + 0,0658445*Ia*Ua - 0,0380435*Ia*v - 0,0747283*Ia*l - 0,679945*Ua*v - 0,348558*Ua*l + 1,02679*v*l

Figure 8. Hardness values difference between the base material (BM) and heat affected zone (HAZ).

Evaluating the results one can notice the following:

• the range of the experimental investigation domain included both stable and less unstable process parameters combinations which lead to the appearance of imperfections especially lack or impartial penetrations and appearance of undercuts which may lead to unacceptable results in terms of quality; these occurrences could be related to some extreme combinations of the process parameters combinations; the provided data, however, was relevant as input for the KBS system and used for training the logic of the system;

• the welding speed is the main influence factor that can increase the hardness difference, inside the investigated experimental domain, with impact onto the acceptability of the mechanical properties if the joint – one of the main quality indicators;

• for the MB-FM hardness difference one can notice an important influence of the welding voltage which is related to how concentrated is the arc energy;

• for the MB-HAZ hardness difference another important influence factor is the welding current which can be correlated with the total energy input and hence the energy flow and heating / cooling cycle speed of the material;

• the generated correlations were used for the KBS system but they can also be used outside the system for selecting combinations of process parameters with specific outcome.

4. Conclusions

A factorial experiment was designed and conducted for realizing 8mm thick T joints of structural steel the GMAW process for generating data inputs for a knowledge based system accompanied by specific destructive and non-destructive testing in order to underline the influence of the welding parameters onto the structural and mechanical characteristics of the joint.

The experimental work provided relevant information in respect to the process stability and occurrence of imperfections for the selected experimental domain determined by four process parameters, mainly undercuts, spattering (high value welding current) and incomplete penetration (at low welding currents or too low compared to the welding speed).

The statistical correlations that were established after the processing of the mechanical testing work were used in the knowledge based system development but can also be sued by designers or welding engineers in the selection and adjustment of their own technologies used in realising welded structures.

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Project - PN 19 36 02 01

Research on the development of the principle of additive manufacturing, 3d printing, by developing innovative modelling equipment by ultrasonic thermoplastic extrusion

Project manager: **Dr. Eng. Nicușor-Alin SÎRBU**
Development period: **2019 - 2022**
Project funded by : **Ministry of Research and Innovation / Ministry of Education and Research**

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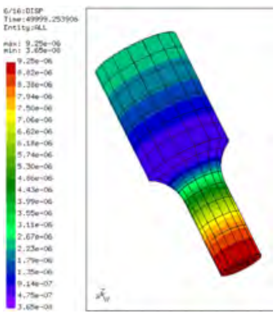
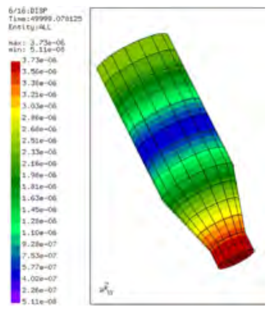


Purpose

- **The project aims to develop an innovative concept of additive manufacturing - Ultrasonic Fused Deposition Modeling (U-FDM)**
  - U-FDM - The classical additive manufacturing by 3D printing (FDM - Fused Deposition Modeling) is combined with the ultrasonic activation technique;
  - The new manufacturing method can be used to process polymeric materials (HDPE, ABS, PLA, PVA, PC, PP, PPSU, PPSF, Pa etc.) and / or composites;
  - Fields of application: automotive industry, dentistry, metallurgical industry etc.

Objectives

- Development of the level of knowledge in the field of additive manufacturing through the development of the innovative concept U-FDM;
- Development of specific technologies for given applications, especially in the automotive field;
- Real-time investigation of process parameters using various techniques, including infrared
- measurement;
- Laboratory testing and validation of the innovative U-FDM concept.



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