Possibilities of joining steel S235 using friction stir welding process assisted by TIG

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Keywords

Steel joint S235; friction welding process with rotatable active element; Classic FSW; FSW assisted TIG; hybrid welding process.

1. Introduction

Most steel welding through melting techniques influence mechanical properties in a negative way because phase changes occur in the base metal microstructure as well as in the metal composition of the welded joint due to the additive material. Applying FSW to high melting temperatures metals is difficult due to the high operating temperatures (1000˚C - 1200˚C) that the tools must resist to, as well as due to the low thermal conductivity and in some cases high resistance to flow of the material [1]. FSW welding of steel sheets is of particular interest because it reduces distortion and a "clean" welding (without pores, inclusions, etc.). Applying FSW to steel requires specific precautions that are mainly targeted: evaluation of FSW equipment, develop the working procedures, demonstrate the feasibility of FSW for different steel grades, evaluation of productivity and welding results [2]. Worldwide studies have shown that low- or medium-carbon ferrous alloys can be welded through FSW process. In these studies, it is stated that the core grain is refined, on carbon steels, similar to Aluminum alloys [3]. It has been demonstrated that when applying FSW to carbon steels, refining the granulation in the core is obtained, similarly to aluminum alloys [4]. Also, these studies show that complex phase transformations occur during FSW welding and the mechanical properties have been improved related to the base metal. In order to improve the severe application conditions of FSW welding, a new hybrid welding method was developed, namely TIG assisted FSW (Figure 1 and 2) [5]. The two processes are carried out simultaneously; the TIG process assures preheating the welding materials, while FSW performs the proper joint.

Figure 1. FSW-TIG Hybrid Welding Assembly

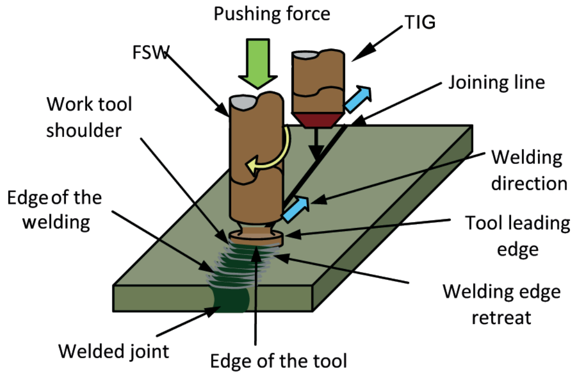

Figure 2. Scheme of FSW-TIG process

Preheating the area near the FSW welding tool results in better plasticization of the welding materials, because heat is generated by an additional heat source (due to the TIG process). After preheating, the joint is developed by FSW [6].

2. Welding material

In the experimental program, a 3 mm thick sheet of steel S235JR + N (delivered in a normalized state) was used.

Table 1. shows the chemical composition and Table 2. shows the mechanical features.

Table 1. Steel S235 JR+N chemical composition (according to Quality Certificate)

Element	[%]	Element	[%]	Element	[%]
C	0.1	Si	0.010	N	0.008
Mn	0.576	Al	0.055	Ni	0.011
P	0.011	Cr	0.018	Si+2.5P	0.038
S	0.016	Cu	0.017	Fe	rest

Table. 2 Steel S235 JR+N mechanical features

R_m, [N/mm²]	$R_{p\,0,2}$, [N/mm²]	A, [%]
416	327	37

S235 JR+N steel as basic material exhibits good ductility and shows a high degree of deformability. It is generally used for the construction of welded structures [7].

3. Experimental conditions

3.1. Technological welding system

In order to develop the FSW experimental program, FSW-TIG was used a complex technological system with the following composition (Figure 3):

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- Welding machine FSW (Figure 3, Pos.1) with the following technical characteristics:

- adjustable welding speed in the field of: 60 - 480 mm/min;
- the speed of the adjustable welding tool in the field of: 300 - 1450 rot/min;
- useful stroke (welding): 1000 mm.

- TIG welding source (Figure 3, Pos.2) with TIG welding source control module (Figure 3, Pos.4), integrated in FSW machine drive and control unit, TIG welding head (Figure 3, Pos.3), gas supply system - monitoring and controlling system for the welding process using infrared thermography (Figure 3, Pos.5).

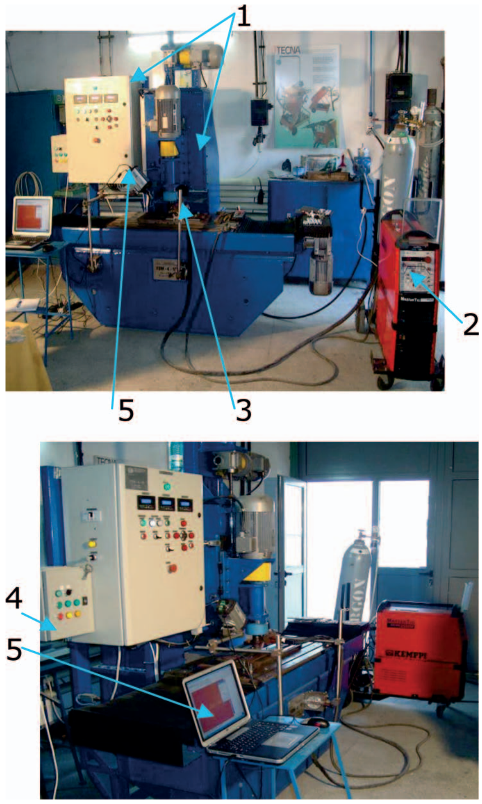

Figure. 3 FSW-TIG Hybrid Welding System.

3.2. Welding tools

Applying classic FSW welding to steels and other materials involving high working temperatures is limited by identifying a suitable material for welding tools that have to withstand temperatures above 1000°C [8].

For FSW welding of S235 JR + N steel thickness s = 3mm, P20S, tungsten sintered carbide welding tools.

P20S material is a quaternary carbide made from a mixture of tungsten carbides, titanium carbides, tantalum and niobium as well as cobalt. If the non-sintered material, in the form of a powder has a density of 2,65 g/cm^3, following sintering at 1400˚C, the material obtained has a density of 12,05 g/cm^3.

P20S material has a hardness of 1500 HV, maintains its properties at 1200-1300˚C and is wear-resistant [9].

Two welding tools geometry have been experimented - Figure 4:

- Smooth shoulder tool Ø=20mm and tapered pine smooth,
- Smooth shoulder tool Ø=20mm and pine with four plane bevels.

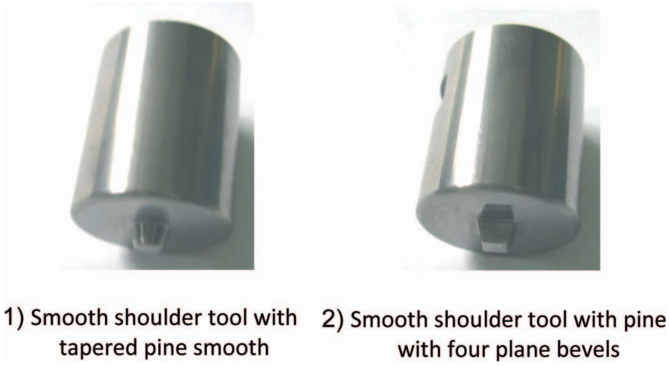

Figure 4. Welding tools made of P20S material

In both cases the length of the pine had values in the range 2.75 - 2.80 mm.

4. Experimental Program

The experimental program aimed at investigating the possibilities of applying FSW-TIG and FSW-TIG to joining steel sheets S 235, thickness s = 3mm, dimensions 400x110 mm. At the same time, a comparative analysis of results obtained using classic FSW process, namely the innovative FSW-TIG hybrid process was performed.

Welding plates have been positioned head to head and fixed, rigidly, on a steel support plate, welding made in the rolling direction.

Welding parameters:

- FSW: v=20-40mm/min, n=700-900rot/min;
- FSW-TIG: v=40-130mm/min, n=700-900rot/min;

In order to obtain quality welds with a well-consolidated core over the entire thickness of the materials, it is necessary to reach optimal plasticizing temperature level. The temperature evolution was followed on-line on the diagrams obtained using an infrared thermography system. Temperature measurements were made in the area of the joint line at a distance of 1 mm behind the welding tool shoulder.

Welded plates were visually examined with penetrating liquids. Both BSW and FSW welding samples were taken, perpendicular to the joint line and bending and static traction tests were performed to determine the mechanical properties of the welds.

Welded joints have been analyzed from a macro and microstructure point of view. The evolution of the hardness in the areas characteristic of the FSW joint was followed and the roughness measured on the surface of the welded joint. The results obtained were compared with those of the base materials.

5. Results and discussions

For classic FSW welding, best results were obtained using the following parameters:

- Welding speed: v=20mm/min,
- Tool speed: n= 800 rot/min.

Thermographic camera records revealed a relatively steady rise in temperature from the beginning of the welding process (from the moment the tool's shoulder contacts the welded parts ~ 500°C and stabilizes at ~ 900°C).

Macroscopic analyzes have demonstrated both lack of defects and a consolidated core in the center of the weld.

To analyze the effect of P20S material, from which the welding tool is made, on the welded joint, its chemical composition was analyzed. The welded joint compared to the base metal contains elements of the welding tool composition, as a result of its wear during the welding process (W - 0.5 - 1.25%).

At static traction tests, the samples broke in the base material at approximately 35-40mm from the joint line. The welded FSW steel joints S235JR + N at the static bending test attest to a maximum degree of deformability (both for the conical pine and the four-chamfer welding tools). Microstructure analyzes have shown that the ferrite matrix is finished by FSW welding (due to plastic deformations), resulting in hardness increase (with ~ 20-25%) in the welded joint.

The main shortcomings in FSW welding steels were:

- excessive wear of welding tools or pin shearing / shearing;
- low welding speeds (~ 20mm/min);
- high welding time / length unit, due to low welding speeds causes excessive heating of the FSW machine and FSW machine main shaft bearings.

Considering these aspects, applying FSW-TIG to welding steels was mainly aimed at increasing productivity by increasing the welding speed, but also protecting the FSW machine and tools.

At FSW - TIG hybrid welding, the results obtained were analyzed using the parameters presented in Table 3.

The best results in terms of the characteristics of welded joints were obtained with the smooth conical pine tool.

Results of static traction tests for welded joints using the flat four-chamfren pendulum tool revealed that the sample taken at the beginning of the FSW process after the 50mm welding had broken into ZITM, probably due to the fact that the welding process did not stabilized (the optimal plasticization temperature of the material has not been reached).

The constructional shape of the welding tool provided a lower coefficient of friction than the smooth conical pendulum, the sharp edges due to the bevels „tearing" pieces of the welding materials. This, even if it is beneficial for the life of the welding tool, at the same time has delayed the process of plasticization of the material. The appearance of the welded joint with a conical pine tool is shown in Figure 5. Very good quality of the surface of the welded joints was obtained, the roughness values being in the range of Ra = 0.54-1.12 μm.

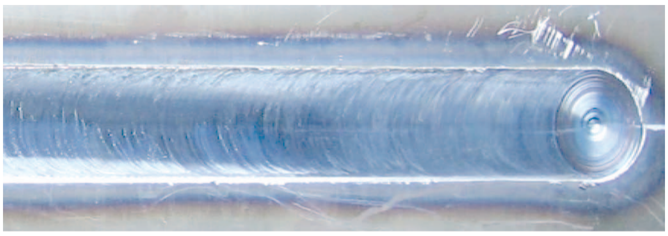

Figure 5. The appearance of the FSW-TIG welded joint with a smooth conical pine too (v=40 mm/min)

Macroscopic cross-sectional images (Nital attack 10%) show that welds without defects or imperfections were obtained, the core being well consolidated at the center of the welded joint (Figure 6. and Figure 7.).

Figure 6. Welding FSW-TIG steel S235 JR+N, v=40mm/min

Figure 7. Welding FSW-TIG steel S235JR+N, v=100mm/min

The temperature evolution diagram during the FSW-TIG welding process is shown in Figure 8.

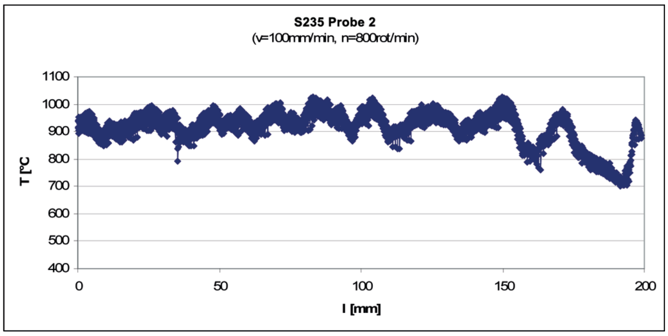

Figure 8. The evolution of welding temperature FSW-TIG steel S235JR+N, v=100mm/min

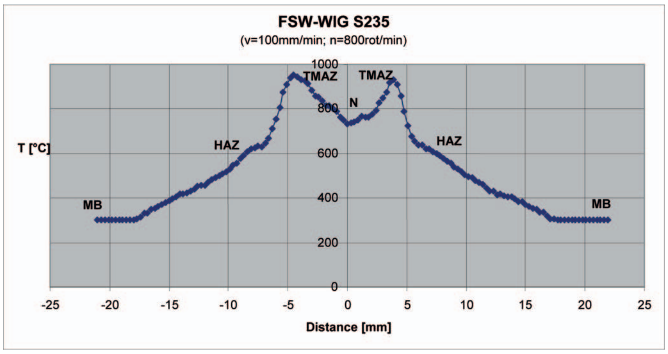

Figure 9. The temperature in the plane perpendicular to the joint line at l = 390 mm from the beginning of the process

At a welding speed v=100mm/min (Figure 8.), the average temperature in the process is approximately 950°C.

In the static traction test, the samples broke in the base material at approximately 30-35mm from the joint line for both

Table 3. FSW parameters and TIG parameters, steel S235 JR + N

FSW			TIG				
Geometry tool	Speed [rpm]	Welding speed [mm/min]	Is [A]	Us [V]	Argon flow [l/min]	Distance* [mm]	Current type
Conical pine / smooth conical knife tool	800	40; 100	100	10.6	6	43.5	CC

* refers to the distance between the axis of rotation of the welding tool and the tip of the tungsten electrode of the TIG welding head.

welding experiments (v_1=40mm/min, v_2=100mm/min), Figure 10. It is possible to follow the temperature evolution in the transverse plane perpendicular to the direction of movement of the welding tool in the areas characteristic of the FSW modeling process. The highest temperatures are recorded in TMAZ-HAZ, reaching a minimum of about 960˚C. In the core the temperature has values in the range 720-800˚C, and in ZIT the average temperature is approximately 600˚C.

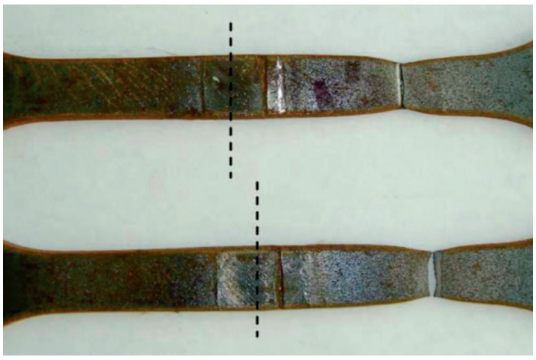

Figure 10. Static drag tests v_2=100mm/min v=40mm/min welding FSW-TIG steel S235JR+N

Figure 11. Samples welded with welding FSW-TIG steel S235JR+N.

Welded FSW-TIG joints at the static bending test show a degree of maximum deformability. (Figure 11).

The hardness HV5 variation diagram for FSW-TIG is presented below. Values go down in HAS and TMAZ, reaching for values close to the base material.

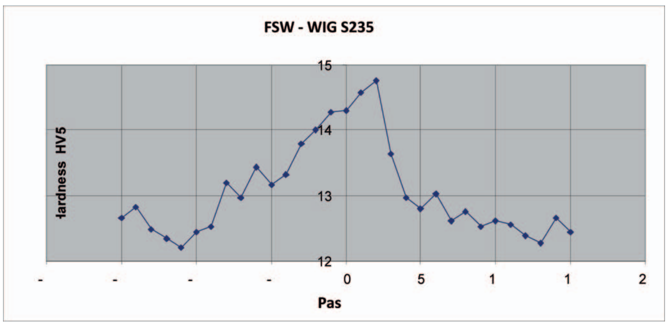

Figure 12. Variation of HV5 hardness on center line at Sample 1 FSW-TIG S235

Figure 13 reflects welding tools in the initial state (before welding), after conventional FSW welding and FSW-TIG hybrid welding (after having achieved approximately 400mm welding in both cases).

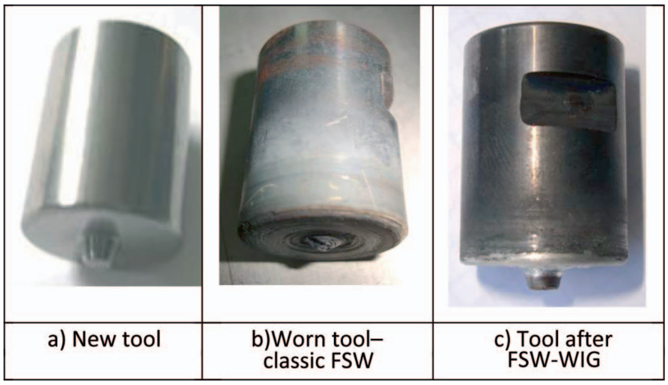

Figure 13. Welding tools before and after welding FSW / FSW-TIG

It can be noticed that when welding the classic FSW, the tool was almost completely destroyed, the application of the FSW-TIG hybrid process was minimal.

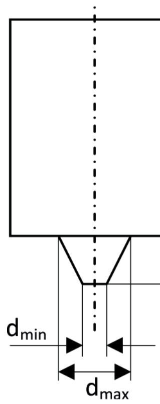

Figure 14. Draft size welding tool

The wear degree of the tool was evaluated by measuring the d_{min}, d_{max} and h dimensions according to the sketch in Figure 14. The results of the measurements are shown in Table 4.

Table 4. Welding Tool Dimensions

Initial dimensions			Dimensions after welding		
d_{min} [mm]	d_{max} [mm]	h [mm]	d_{min} [mm]	d_{max} [mm]	h [mm]
4.00	5.00	2.85	3.90	4.85	2.56

For FSW-TIG welding, the wear was approximately 2,5% for dimensions dmin şi dmax, and approximately 10% for the h-size of the welding tool.

6. Conclusions

FSW welding steels, it is necessary to provide additional conditions, especially with regard to the characteristics of the FSW system and welding tools (higher forces, increased stiffness), compared with welding of lightweight alloys (Al, Mg). The behavior at FSW of steel S235 JR + N is very good considering the use of the new optimized welding parameters.

The comparative analysis of results obtained in FSW classic welding, namely FSW-TIG of S235 steel, highlighted several relevant aspects:

- excellent mechanical properties of welded joints have been achieved when applying both processes;

- in comparison to the FSIM welding technique available in ISIM Timisoara (welding machine and machine tools); the welding speeds (up to 500%) could be used compared to the conventional method.
- wear of welding tools decreased significantly in FSW-TIG welding.

W-sintered carbide tools can be used to develop research and demonstration programs of the FSW process for welding steel S 235 JR + N, but are not a solution for industrial applications due to reduced lifetime (high wear).

References

[1]. H. Fujii, L. Cui, N. Tsuji, M. Maeda, K. Nakata, K. Nogi - Friction stir welding of carbon steels, Materials Science and Engineering A 429 (2006) 50–57

[2]. AK Lakshminarayanan, V Balasubramanian, M Salahuddin- Microstructure Tensile and Impact Toughness Properties of Friction Stir Welded Mild Steel, JOURNAL OF IRON AND STEEL RESEARCH, INTEF3'JATIONAL. (2010), 17(10): 68-74

[3]. T. J. Lienert, W. L. Stellwag, jr., B. B. Grimmett, and R. W. Warke- Friction stir welding studies on mild steel, Supplement to the WeldingJjournal,January 2003, page 1s-9s

[4]. [4] R. Mishra, M.W. Mahoney- Frictio Stir welding and processing, ASM International, 2007, ISBN -13 978-0-87170-840-3

[5]. R. Nandan, T.DebRoy, H.K.D.H. Bhadeshia - Recent Advances in Friction Stir Welding – Process, Weldment,Structure and Properties, Progress in Materials Science 53, 980–1023, (2008)

[6]. Brevet de invenție „Sudare hibridă FSW-TIG", Hotărâre OSIM Bucureşti Nr. 4111/30.05.2011

[7]. R. Cojocaru, L.Boțilă, C.Ciucă - Friction stir welding of S235 steel, 15th ModTech International Conference Modern Technologies, Quality and Innovation New Face of TMCR, 25-27 Mai 2011, Chișinău, Republica Moldova

[8]. A.P. Reynolds, W. Tang, M. Posada şi J. DeLoach, Friction stir welding of DH 36 steel, Science and Technology of Welding and Joining, Vol. 8 No. 6 / 2003

[9]. R. Cojocaru, L.Boțilă, C. Ciucă, Comportarea la sudarea cu element activ rotator a oțelului S420MC, Buletinul Institutului Național de Cercetare-Dezvoltare în Sudură şi Încercări de Materiale Timişoara (BID-ISIM) – Sudarea şi Încercarea Materialelor, 4, (2014), pp. 13-17