Impact of using inert gas to friction stir welding of DD13 steel

Lia-Nicoleta BOȚILĂ[1,a], Radu COJOCARU [1,b] and Horia-Florin DAȘCĂU[1,c]

1National Research& Development Institute for Welding and Material Testing - ISIM Timișoara,

30, Mihai Viteazu Blvd., 300222, Romania

[a] *lbotila@isim.ro,* [b] *rcojocaru@isim.ro,* [c] *hdascau@isim.ro*

Keywords

Friction stir welding, shielding gas environment, DD13 steel

Abstract

Friction stir welding (FSW) is in a continuous development, being used in various applications in top industrial fields. Complex research conducted in various research centers and world-renowned industrial companies is carried out on several research directions.

ISIM Timisoara has been researching the FSW welding process for several years, obtaining important results communicated at international conferences or published in specialized journals, respectively several original ideas that have patented or are being patented.

The paper presents some results obtained by ISIM Timișoara regarding the friction stir welding in inert gas environment (FSW-IG). The experimental research program was carried out within an ongoing national research project. Welding experiments of DD13 steel were performed by the FSW-IG and FSW process, respectively, in the same welding conditions (equipment, welding tool, technological process parameters), in order to substantiate the comparison of the obtained results.

The comparative analysis performed after the evaluation process of the welded joints using the FSW-IG method and the classical FSW process, shows an improvement in the quality of welded joints by FSW-IG method, compared to the classical FSW, mainly from the following points of view: reduction with approx. 10% of heat affected zone around the shoulder of the welding tool, minimizing the possibilities of forming of intermetallic compounds, as well as the reduction the possibilities to occur of defects in the welded joint, which is an important condition for obtaining some mechanical characteristics in welding, close to those of the base material.

1. Introduction

The joining of steels by conventional electric arc welding processes leads to the achievement of very high welding process temperatures, as well as important changes in the microstructure and mechanical properties of the welded metal. Conventional (electric arc) welding of steels involves a number of costs related to filler materials, welding consumables, protective equipments, etc.

Friction stir welding is an ecological process of joining materials, which takes place in a solid state, at temperatures of max. 80% of the melting temperature of the materials to be joined, with no filler materials. The simplicity of the process, the possibilities of automation, the impact on the environment and health, as well as the economic efficiency, recommend the FSW process as an alternative to the classic electric arc welding processes of steels.

There is considerable interest in applying this joining technology to steels, although most FSW research has generally focused on aluminum alloys.

Worldwide research has been conducted on FSW welding for a wide variety of steels: with very low carbon content, with low, medium, high and very high carbon content, stainless steels, special steels, superalloys, etc. [1].

In recent years, at worldwide level, remarkable progress has been made in FSW welding of steels, in all aspects regarding technical requirements for welding equipments, the development of suitable FSW tools for joining of steel (tools made of high mechanical strength materials, with high temperature resistance and high wear resistance), new and innovative working techniques, systems and methods for welding processes monitoring and control, respectively evaluation of the microstructure and properties of welded joints.

All of these contributes to reach a new level of technical maturity in FSW welding of steels, being able to obtain high quality welded joints, long length of welds, for a large number of steels used in applications in engineering [2].

Friction stir welding is included in the research programs of ISIM Timisoara, being carried out complex research on the application of this process to join (as similar and dissimilar materials) aluminum alloys, copper, magnesium, titanium and steels.

Regarding the FSW welding of steels, this field is of great interest for ISIM Timisoara. Thus, in some research projects, ISIM has developed its own experimental research programs on FSW welding for different types of steels, obtaining very good results in FSW welding of S235 steel, S420 steel and AISI 304L stainless steel (fig.1), as pairs of similar materials with thicknesses s = 1.5 - 3 mm [3]- [5].

The experimental programs developed for welding steels S235, S235JR + N (SR EN 10025: 2019), S420MC (SR EN 10149: 2014) and AISI 304L (SR EN 10088: 2015) have demonstrated their good behavior when applying the FSW process, in the conditions of respect the correct principles regarding: FSW welding machine, parameters used and geometric and dimensional characteristics of the welding tools.

S235
[3]

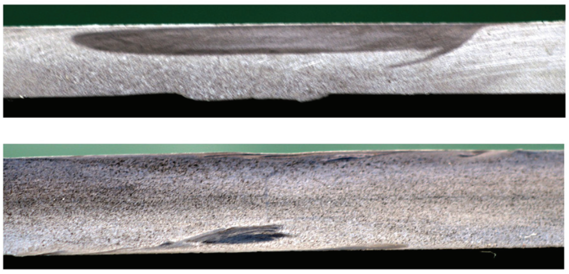


Fig. 1 Macroscopic appearance of welded FSW joints - steels

This paper addressed the problem of welding DD13 steel (SR EN 10111: 2008) used in the automotive industry, in the variant of using FSW welding in a shielding gas environment compared to the classic FSW process, in order to analyze the impact it has the application of inert gas to welding on the quality of welded joints.

2. Experimental FSW-IG welding program for DD13 steel

The experimental welding program was designed to perform welded joints by using FSW process in a shielding gas environment (FSW-IG) and classic FSW process, for DD13 steel sheets, with aim to make a comparative analysis of the obtained results and highlight the impact of the application of the inert gas environment on the structural analyzes and on the mechanical characteristics of the welded joints.

2.1 Welding technique

The experimental welding program was performed on the friction stir welding machine FSW-4-10 from the ISIM Timisoara endowment, having the main characteristics presented in tab. 1.

Table 1. Main characteristics of the FSW-4-10 machine

Main characteristics	Value / value range
welding speed	adjustable, 10-480 mm/min
tool rotation speed	adjustable, 300-1450 rot/min
engine power for FSW welding tool rotation	4 kW
useful stroke (welding)	1000 mm
welding machine table	1000 x 510 mm
welding length	max. 800mm

In order to be able to use FSW welding in inert gas environment, it was necessary to be designed technical solutions of modules / devices to complete the FSW welding machine and ensure the supply of inert gas in the welding area.

Several variants of applying inert gas to FSW welding have been proposed:

- unidirectional application of shielding gas to welding, in front or behind of the welding tool, through a gas nozzle fixed on a mounting bracket and a shielding gas supply system (variant 1);

- circular application of the shielding gas (variant 2). In this case, the shielding gas supply to the working area is made by a system which ensures a uniform distribution of the inert gas flow around the tool through several holes positioned equidistantly on a circular contour around the welding tool. The circular system for the uniform distribution of the shielding gas is mounted on the main shaft of the FSW welding machine, using a positioning and fixing plate;

- gas enclosure, mounted on the main shaft of the FSW welding machine (variant 3). The role of the enclosure is to ensure that the inert gas is maintained at the prescribed pressure during the FSW-IG welding process (in the contact area between the welding tool and the materials to be welded). The shielding gas enclosure is located on the main shaft of the FSW welding machine. The enclosure has the side walls made of transparent material that allows real-time visualization of the FSW process;

- gas application enclosure, mounted on the table of the FSW welding machine (variant 4). This enclosure has a fixed cover (mounted on the main shaft of the welding machine) provided with an element that ensures the access of the thermographic camera lens directly inside the enclosure, thus making it possible to view and focus the welding area. This constructive variant of applying inert gas to FSW-IG welding offers the possibility to monitor the welding process without the walls of the enclosure being an obstacle in this respect.

Constructive variants for the application of inert gas have been proposed in order to cover all the characteristics and the process requirements related to FSW-IG welding regarding:

- the optimal gas supply mode;
- the required volume of inert gas in the working area;
- ensuring the process parameters in similar conditions to the classic FSW welding;
- possibilities to apply solutions for monitoring the FSW-IG welding process

The constructive variants 1 and 2 of the devices for providing shielding gas in the welding area are simple solutions that ensure the presence of inert gas in the welding area only in the immediate vicinity of the welding tool that is in contact with the materials to be welded. Both variants allow the visualization and direct monitoring, without obstacles, of the welding process.

In the experimental FSW welding program in inert gas environment for DD13 steel, the FSW welding machine (fig. 2a) was used, having the variant 3 (enclosure type) of inert gas supply in the welding area, which is mounted on the main shaft of the FSW machine (fig. 2b).

The result is an FSW-IG welding system comprising the FSW welding machine, the shielding gas enclosure with the gas supply system, as well as specialized FSW welding tools.

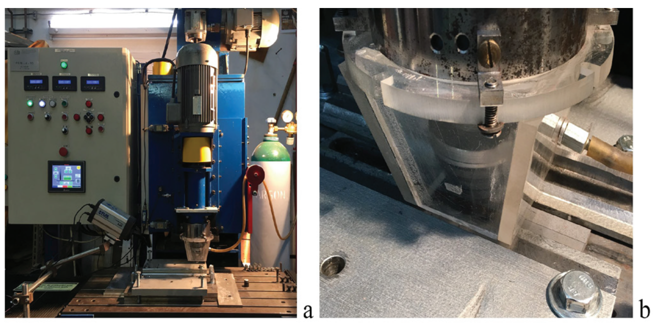


Fig. 2 FSW machine with variant 3 (enclosure type) of applying inert shielding gas to welding (a) and detail-enclosure (b)

Compared to FSW welding of non-ferrous materials, FSW welding of steels requires welding tools made of high durability materials, which can withstand to higher temperatures, but also to high forces developed during the welding process.

Considering that in some preliminary researches of FSW welding of DD13 steel, good results were obtained using a welding tool made of sintered tungsten carbides P20S, with smooth conical pin and smooth shoulder (Øshoulder=20mm), it was proposed to use this tool geometry (fig. 3) in the experimental FSW-IG welding program of this steel.

The tool material, P20S, is a mixture of carbides (of tungsten WC, titanium TiC, tantalum TaC, niobium NbC) and cobalt Co, obtained by sintering at 14000C. P20S is a material with very high hardness (1500HV), which has thermal stability up to 1200-13000C.

Fig. 3 Welding tool with smooth conical pin

An important element for the good development of the friction stir welding process is represented by the pin length of the welding tool, which must be correlated with the thickness of the materials to be joined.

For friction stir butt welding, the pin length of the welding tool can be approx. 0.84-0.95 of the thickness of the materials to be welded.

For example, at the FSW butt welding of sheets having 2.2 mm thickness (DD13 steel, in this case), welding tools with pin length L_{pin} = 1.85 mm were used.

2.2 Welding materials and process parameters

The experimental program of friction stir welding in inert gas environment FSW-IG and FSW welding (classic) was made for DD13 steel sheets having 2.2 mm thickness and 250 mm x 100 mm dimensions of the sheets.

DD13 steel (1.0335) is a low carbon steel (according to SR EN 10111: 2008), used in the automotive industry (for parts obtained by cold forming or stamping), with chemical composition and mechanical properties [6, 7] presented in tab. 2.

Table 2. Chemical composition and mechanical characteristics for DD13 steel

Element	**C**	**Mn**	**P**	**S**	**Fe**
%, max.	0,08	0,4	0,03	0,03	balance
Rm, N/mm²	360-400				
Rp0,2, N/mm²	170-300 (for 1-2mm material thickness) 170-310 (for 2-11mm material thickness)				
A, %	27 (for 1-1.5mm material thickness) 28 (for 1.5-2mm material thickness) 29 (for 2-3mm material thickness)				

DD13 steel has a low carbon content, being a soft steel with high plasticity, easy to be processed. The melting temperature of DD13 is 1480-15260C, its density being 7.8-7.9 g/cm3, both falling within specific ranges of steels. DD13 steel has high mechanical strength, good casting properties and good weldability. The maximum industrial operating temperature of parts made of DD13 steel is 5000C.

This steel can be widely used in the automotive industry (in the manufacture of chassis, parts for seats and various parts for vehicles), as well as in other industrial fields (e.g. components for construction, precision tubes, components for furniture, etc.) [8].

The FSW-IG and FSW welding experiments were performed under the same process conditions, in order to be able to make a comparative analyze of the obtained results.

The purpose of comparing the results is to analyze the effect (impact) of using inert gas working environment on the friction stir welding of DD13 steel, compared to classical FSW (in air working environment).

At the FSW–IG welding, argon was used as an inert shielding gas, at a flow rate of 16 l / min.

Technological parameters of FSW– IG and FSW welding processes are presented in tab. 3.

Table 3. Technological parameters for FSW-IG and FSW - DD13

Welding process	**Tool rotation speed n (rot/min)**	**Welding speed v (mm/min)**	**Inert gas flowrate (l/min)**	**Tool rotation sense**
FSW-IG	800	20, 40, 60, 80	16	counter-clockwise
FSW	800	20, 30, 40, 60, 80	-	

In case of both FSW-IG inert gas welding experiments and FSW welding experiments, a constant welding tool rotation speed of n=800 rot/min (counterclockwise rotation) was used, respectively variables welding speeds in the range vs=20-80 mm/min.

Welding speeds have been gradually increased in both cases (FSW and FSW-IG welding) in order to identify application limits from this point of view.

2.3 Welding experiments and welded joints evaluation

In order to analyze the impact of using inert gas in FSW-IG welding on the quality of the welded joint (structural analyzes and mechanical characteristics of the joints), welding experiments of DD13 steel were performed by FSW-IG and FSW process, respectively, in the same welding conditions presented in Chapter 2 (equipment, welding tool, technological process parameters), in order to substantiate the comparison of the obtained results.

The evaluation and characterization of FSW and FSW-IG welded joints includes: visual examination of joints, macroscopic and microscopic structural analyzes, hardness measurements for base material (BM) and for welded joints, tensile and bending mechanical tests, as well as analysis of results obtained for joints FSW-IG welded compared to FSW welded joints and BM.

The appearance at the surface and at the root of the welded joints FSW and FSW-IG are shown in fig. 4 and 5.

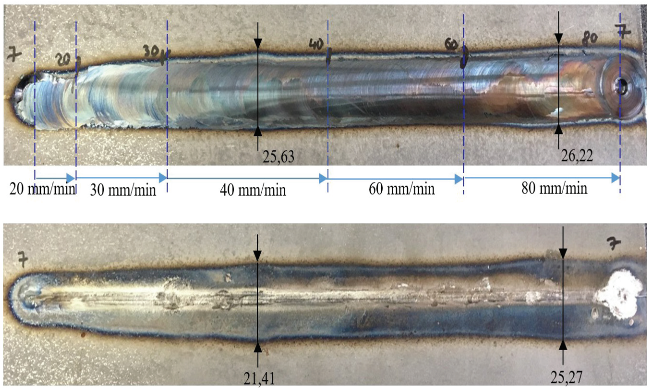


Fig. 4 Appearance of FSW welded surface and root, DD13 steel

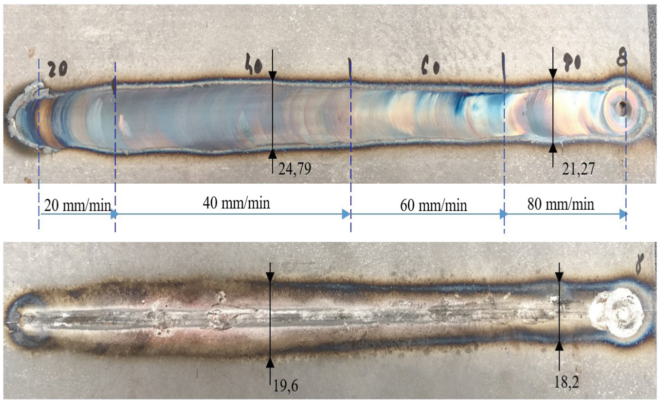


Fig. 5 Appearance of FSW-IG welded surface and root, DD13 steel

Analyzing the appearance on the surface of the welds made by FSW (fig. 4) and FSW-IG (fig.5), it is observed that, in both cases, after the stabilization of the welding process, at approx. 20-25 mm from the beginning of the welding process, a joint with good surface appearance, without major defects, was obtained. Comparing the dimensional measurements performed at the surface, respectively at the root of the FSW and FSW-IG welded joints, it was found that the heat affected zone around the welding tool shoulder is wider at FSW welding compared to FSW-IG welding (at the welding surface and welding root).

The monitoring of the forces developed during the welding process was possible by using the system that indicates the evolution of the force values with which the tool shoulder presses on the joining materials. The force monitoring showed that during the FSW and FSW-IG welding processes, depending on the process phase, the maximum values of the pressing force were between: F_{max} ~ 5.700-6.100N (in the plunge phase of the welding tool pin in the materials to be joined), F_{max} ~ 5.850-7.200N (at the start of longitudinal feed for welding) and F_{max} ~ 5.800-7.100N (during the welding process).

Specimens for structural analysis and hardness measurements, for mechanical tensile tests and bending tests, were taken from the FSW and FSW-IG welded joints. Sampling, processing and preparation for metallographic analyzes was performed according to STAS 4203-74, and the attack with chemical reagents, according to the norm SR CEN ISO / TR 16060: 2015. The macroscopic examination method was based on SR EN ISO 17639: 2014 and SR EN ISO 25239-5: 2011.

Figure 6 shows the macroscopic appearance of the FSW and FSW-IG welded samples, taken from areas where welding speeds of: 40 mm/min, 60 mm/min and 80 mm/min, respectively, were used.

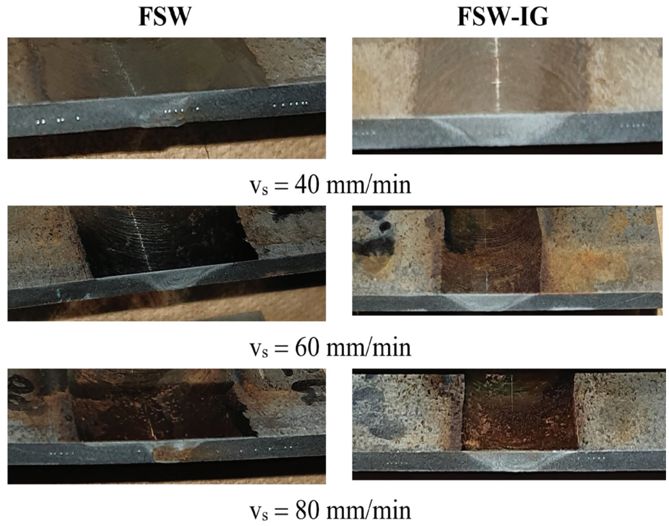


Fig. 6 Macroscopic appearance of FSW and FSW-IG welds

Analyzing the macroscopic aspect of the samples taken from the joints made by FSW and FSW-IG (fig. 6), it is observed that for all welding speeds that are used (40 mm/min, 60 mm/min and 80 mm/min), "clean" welds with no visible defects at the macroscopic level were obtained. At FSW welding, with the increase of the welding speed to 80 mm/min, it is observed an area in which the appearance of possible intermetallic compounds is highlighted.

Microscopic examination of specimens taken from FSW and FSW-IG welded joints was performed in accordance with SR EN ISO 17639: 2014, SR EN ISO 6520-1: 2007, SR 5000-97, STAS 5500-74, respectively SR EN ISO 643: 2013.

Microstructural analyzes of samples taken from welded joints made by using FSW and FSW-IG were performed using an optical microscope at 100X magnification. These microstructural analyzes (fig.7) show that in both FSW and FSW-IG welded samples, the BM structure consists of ferrite, pearlite and pearlite in rows, and the structure in the heat affected zone (HAZ) contains ferrite, pearlite, acicular and networked ferrite. In HAZ, but especially in the nugget, there has been a considerable reduction in grains size and therefore a microstructural finishing.

In the nugget of the classical FSW welded joint, unlike FSW-IG welding, well-marked areas of possible intermetallic compounds were formed, regardless of the value of the welding speed used. This indication may lead to the conclusion that the use of inert shielding gas in FSW welding may help to reduce or even prevent the formation of intermetallic compounds in the welded joint.

The evaluation program of the welded joints also included measurements for determining the HV5 hardness (according to SR EN ISO 6507-1: 2006) in cross section of the joints made by classical FSW and FSW-IG welding.

FSW		FSW-IG		
welded joint	BM	welded joint	BM	welding speed

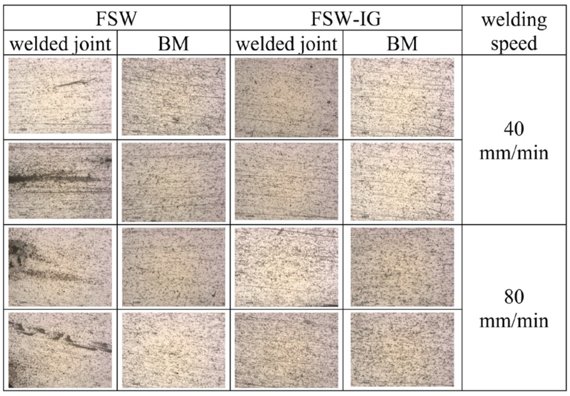


Fig. 7 Microscopic analyze BM, FSW and FSW-IG welded joints

The measurements for determining the hardness values were performed in the median plane of the thickness of the materials to be joined, located at 1.1 mm from the surface (BM thickness is 2.2 mm). The step between measurements was 1mm, both for the welded joint area and for the BM.

The graphs in fig. 8 shows the hardness evolution in classic FSW welded joints, for specimens taken from areas corresponding to welding speeds of 40mm/min, 80mm/min.

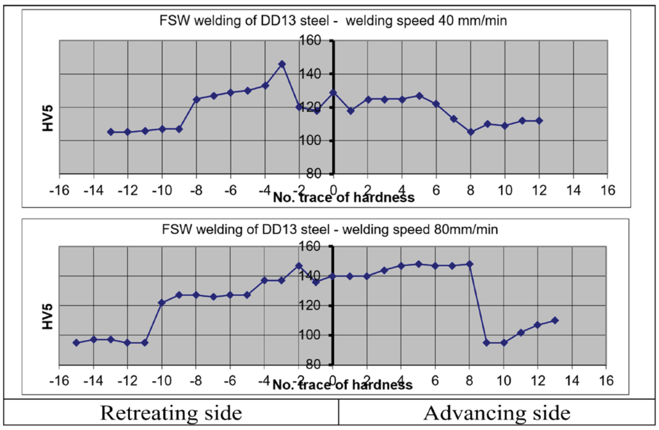


Fig. 8 Hardness graphs–FSW welding of DD13 (40; 80 mm/min)

Analyzing the hardness values and their distribution on the graphs in fig. 8 (classic FSW welding) it is observed that:

- using higher welding speeds (v=80mm/min compared to v=40mm/min), higher hardness values with ~20% in the thermo-mechanically influenced area (TMAZ) and in HAZ on the advancing side of the welding tool, were obtained;
- in the nugget area (N) the measured hardness values are higher in this case by ~ 15%.

The graphs in fig. 9 shows the hardness evolution in FSW-IG joints, for specimens taken from areas corresponding to welding speeds of 40 mm/min and 80 mm/min.

Analysis of the hardness graphs in fig. 9 (FSW-IG welding) highlights the following aspects:

- at the welding speed of 40 mm/min, the average hardness value in the BM is ≈108–110 HV5, the nugget hardness has a higher value (≈137 HV5), the hardness values in TMAZ being 131-135 HV5. Values of max. 146 HV5 were measured in HAZ near interference with TMAZ and with decreasing values towards ± 8 mm away from the joint axis;
- at the welding speed of 80 mm/min, the hardness values in the nugget is ≈137-138 HV5; in TMAZ and HAZ the hardness values were higher, with a maximum of 156 HV5 in HAZ on the retreating side of the welding tool and values close to those in the nugget on the advancing side of the tool.

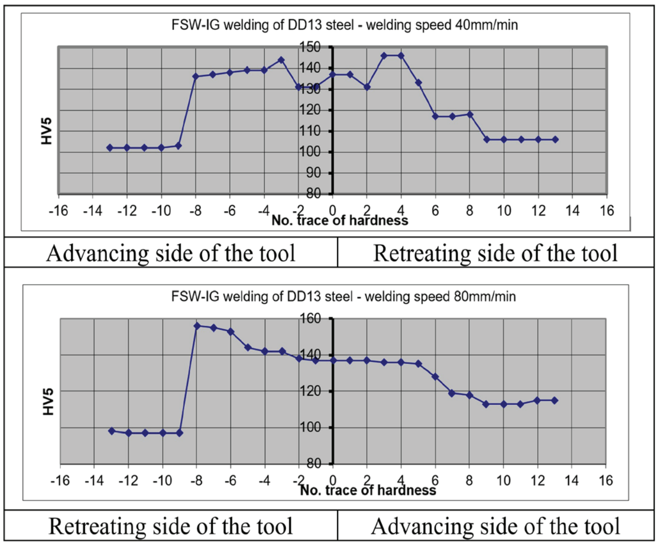


Fig. 9 Hardness graphs -FSW-IG welding of DD13 (40; 80mm/min)

Analyzing comparatively the values of the measured hardnesses for classical FSW and FSW-IG, in correlation with the technological parameters used, it was found that there were no significant differences between them.

All structural analyzes and hardness measurements were performed under ambient test atmosphere conditions (230C) according to STAS 6300-81.

Tensile tests were performed at ambient temperature (230C), in accordance with SR EN ISO 6892-1: 2020 for test specimens taken from welded joints made by classic FSW and FSW-IG, related to the use of welding speeds of 40mm/min, 60mm/min and 80mm/min. The appearance of the specimens after the tensile test is shown in fig.10 (for classic FSW welding) and in fig.11 (for FSW-IG welding).

In fig. 10 it is observed that the specimens (taken from the classic FSW welded joint) corresponding to the use of welding speeds of 40mm/min and 60mm/min, broke in the base material at values of breaking strength Rm~366-367 N/mm2. The specimen corresponding to the welding speed of 80mm/min broke in the weld at a value of breaking strength Rm~361 N/mm2. The breakage may be caused by the presence of fragile intermetallic compounds in the joint. Another cause may be the high welding speed used in this experiment, which could have an insufficient homogenization effect of the weld in the mixing zone (N nugget).

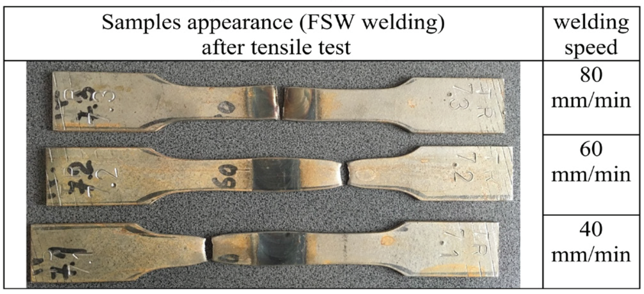


Fig.10 Samples appearance after tensile tests– FSW welding, DD13

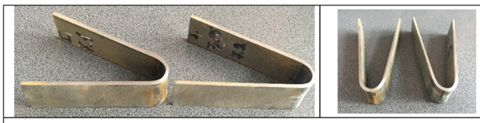
In fig. 10 it is observed that the specimens (taken from the classic FSW welded joint) corresponding to the use of welding speeds of 40mm/min and 60mm/min, broke in the base material at values of breaking strength Rm~366-367 N/mm2. The specimen corresponding to the welding speed of 80mm/min broke in the weld at a value of breaking strength Rm~361 N/mm2. The breakage may be caused by the presence of fragile intermetallic compounds in the joint. Another cause may be the high welding speed used in this experiment, which could have an insufficient homogenization effect of the weld in the mixing zone (N nugget).

Samples appearance (FSW-IG welding) after tensile test	welding speed
	80 mm/min
	60 mm/min
	40 mm/min

Fig.11 Samples appearance after tensile tests- FSW-IG, DD13 steel

It is observed that the specimens taken from the welded joint FSW-IG broke in the base material (fig.11), regardless of the values of the welding speeds used, the specimens being taken from areas where the welding speeds had values of 40mm/min, 60mm/min and 80mm/min.

Bending tests were performed (according to SR EN ISO 5173:2010) with the stretched root (which is the most unfavorable situation) for specimens taken from FSW and FSW-IG welded joints, the results of bending tests being presented in fig. 12. Like the tensile tests, the bending tests were performed in ambient atmospheric conditions (230C).



a) Samples appearance (FSW weld, DD13) after bending tests

b) Samples appearance (FSW-IG weld, DD13), after bending tests

Fig. 12 Samples appearance- bending tests (FSW, FSW-IG welds)

It is observed that for both cases (FSW welding and FSW-IG welding), the deformability degree is maximum (α = 1800) for bending tests with the stretched root.

3. Conclusions

The experimental research program for FSW-IG welding of DD13 steel was carried out using the FSW-4-10 welding machine from the ISIM endowment, equipped with working technique (designed and made at ISIM Timisoara) specific to the application of FSW welding in inert gas environment.

FSW and FSW-IG welding experiments were performed under the same working conditions in terms of welding equipment, welding tools, welding materials and their thicknesses, as well as technological process parameters.

The application of FSW-IG welding to joining of DD13 steel, compared to conventional FSW welding, highlighted the following aspects:

- the heat affected zone around the welding tool shoulder was reduced by approx. 10%;
- the possibility of forming intermetallic compounds is reduced to a minimum;
- the possibility to occur defects in the welded joint is reduced, that is an important condition for obtaining some of mechanical characteristics in the weld, close to those of the base material;
- unlike conventional FSW welding, at the tensile test, all FSW-IG welded samples have broken in the BM, inclusive when increased welding speed (80mm/min) was used;
- FSW welding tool with smooth conical pin proved to be an optimal solution for FSW and FSW-IG welding of DD13.

Research will continue in order to obtain important information on the use of the FSW-IG method compared to the classical FSW, from other points of view (e.g. analysis of fracture surfaces by fractography, residual stresses etc.).

Acknowledgements

The paper was developed based on the results obtained in the frame of the project PN 19.36.01.01 entitled “Research on the development of new innovative methods of application of the friction stir welding process in order to expand the possibilities of application in priority areas”, funded in the frame of the Nucleu Program of ISIM Timişoara (contract 35N / 2019), by the Ministry of Research and Innovation.

References

[1]. Chiteka K. - Friction Stir Welding of steels: A Review Paper, IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) e-ISSN: 2278-1684, p-ISSN: 2320-334X, Volume 9, Issue 3 (2013), PP 16-20

[2]. Liu F.C., Nelson T.W. - A review of friction stir welding of steels: Tool, material flow, microstructure and properties, J. Mater. Sci. Technol., Volume 34, Issue 1, January 2018, pp. 39-57

[3]. Cojocaru R., Boţilă L. N., Ciucă C. - Friction stir welding of S235 steel, The 15th ModTech International Conference Modern Technologies, Quality and Innovation New Face of TMCR, 25-27 May 2011, Chişinău, Republic of Moldova, published in Vol I, pp. 273-276, ISSN 2069-6736, ISI indexed

[4]. Cojocaru R., Boţilă L. N., Ciucă C. - Friction stir welding behaviour of S420Mc steel, Welding& Material Testing, No.4/2014, pp. 13-17, ISSN 1453-0392, Year XXIII, Timisoara, Romania, 2014, BDI indexed

[5]. Ciucă C., Cojocaru R., Boţilă L. N., Perianu I. A. - General considerations regarding friction stir welding of some steels used in important industrial fields, International Conference Innovative Technologies for Joining Advanced Materials TIMA 19, Timisoara, 7-8.11.2019.

[6]. http://www.steel-plate-sheet.com/Sellinglist/DD13-steel-plate-EN10111-DD13-steel-plate-DD13-supplier-DD13-steel-price.html

[7]. http://www.steelnumber.com/en/steel_composition_eu.php?name_id=220

[8]. http://www.automobile-steel.com/Automotive-steel/EN-10111-DD13.html