Friction stir welding behaviour of S420MC steel

R. Cojocaru, L.Boțilă, C. Ciucă

National Research& - Development Institute for Welding ang Material Testing - ISIM Timisoara, Romania

E-mail: rcojocaru@isim.ro

Keywords

Friction steer welding, FSW, S420MC steel, welding parameters, welding behaviour

1. Introduction

The friction stir welding process (FSW) is successfully applied to aluminum joint and other metals with relatively low melting temperatures.

Based on the benefits of friction stir welding aluminum and copper alloys, should obtain similar benefits and cost reduction to application of FSW on high melting temperature metals such steels.

Application of FSW process to steel and other materials that involving high temperatures is limited to the identification of a suitable material for the welding tool, which must withstand temperatures of 1000°C. [1], [2].

Also special precautions are required (compared with FSW welding of Al, Mg light alloys), mainly in terms of the welding machine, which must provide good stiffness properties.

Friction stir welding of steel plates determine a particular interest because it ensures a reduction of deformation and „clean" weld; (without pores, inclusions, etc.).

Application FSW to steel require resolving some of specific problems which are mainly: the assessment of FSW equipment, develop of work procedures, demonstrating the feasibility of FSW to various steel grades, productivity and performance assessments at welding [3]-[5].

Studies conducted at worldwide level in recent years have shown that ferrous alloys with low or medium carbon content can be welded using FSW.

In these studies is indicated that for carbon steels, the grains finishing in nugget is similarly to aluminum alloys.

Preliminary research have demonstrated the feasibility of applying FSW to steel and ferritic stainless steel. Promising results were obtained on the mechanical properties of FSW and also significantly reducing of joint deformations [6].

This paper presents the results obtained at ISIM Timisoara, within an experimental program developed for friction stir welding of S420MC steel, often used in industrial applications, mainly due to the high quality of cold deformation.

2. Material

In the experiments sheet thickness s = 2 mm, 400x110 mm size, was used.

Steel 420MC is part of high strength steels for cold forming, with high yield strength, according to EN 10149-2 „Hot rolled flat products with high yield strength steels for cold forming".

S - steel for construction

Yield strength of this steel is Rp_{02}=420 N/mm^2.

M - thermo laminating

C - special cold forming

The chemical composition of S 420MC sheets, according to the certificates of quality from the supplier (Czech Republic), is presented in Table 1.

Table 1. The chemical composition of steel S 420MC (quality certificate).

Chemical composition, [%]									
C	Mn	Si	S	P	Al	Nb	V	Ti	Fe
0.042	0.78	0.019	0.011	0.013	0.052	0.0159	0.0025	0.001	rest

Table 2 summarizes the mechanical properties of steel S420MC, according to EN 10 149 and certificate of quality from the manufacturer.

Table 2. Mechanical properties of S420MC steel.

	R_m [N/mm^2]	$R_{p0.2}$ [N/mm^2]	A [%]
EN 10149	min. 480 - max. 620	min. 420	min. 16
Certificate of quality	493	447	25.5

Steel S 420MC has superior quality of cold deformation and is used, for example, in manufacturing products through cupping.

3. Experimental program

The experimental program was developed on specialized FSW machine from ISIM Timisoara.

The main characteristics of the machine are:

- adjustable welding speed, in field: 10 - 480 mm/min;
- adjustable rotational speed of the welding tool in field: 300-1450 rot/min;
- stroke (welding): 1000 mm.

The work pieces were butt positioned and fixed rigidly on a steel backing plate, making the welds on lamination direction.

In the first phase of the experimental program, X38CrMoV5 steel alloy heat treated to 52-55 HRC and tungsten alloys with 2% La_20_3 (WL 20) or 2%$Th0_2$ (WT 20) were used as materials for welding tools. Tools were tested also to welding of titanium Ti Gr2 [7].

In the second phase, FSW tools were made of sintered tungsten carbide (P20S) with chemical composition and characteristics presented in Table 3.

From geometric point of view, welding tools with smooth tapered pin and smooth shoulder with Ø = 20 mm were used (Figure 1).

Table 3. Quaternary carbide P20S.

Chemical composition P20S [%]				
Co	TiC	TaC+ NbC		WC
9.00	10.0	5.00		76.00
Powder characteristics				
Particle size [µm]		Powder material density [g/cm³]		
2.0		2.65		
Physical properties of sintered material				
Density of sintered material [g/cm³]		Hardness HV50	Mechanical strength [N/mm²]	
12.05		1500	1650	

Figure 1. Welding tool with smooth tapered pin and smooth shoulder.

Welding speeds in the range v = 20-40 mm/min were used (limited by technical and functional characteristics of the FSW specialized machine from ISIM). Rotational speeds of the welding tool were n = 400-1000rpm and direction of rotation is counterclockwise.

To obtain quality welds with a good nugget, consolidated on the full thickness of welded materials, is necessary to achieve the optimum temperature for their plasticizing.

The temperature evolution was on-line monitored on diagrams obtained by using infrared thermography system. Temperature measurements were made in the joint line at a distance of 1 mm behind the welding tool shoulder [8].

Welded plates were examined visually and with penetrant liquids.

Samples were taken from both base materials and the friction stir welds, perpendicular to the joint line. bending and static tensile tests were performed to determine the mechanical properties of welds.

Welded joints were analyzed in terms of macro and microstructure. To follow the evolution of hardness on FSW joint characteristic areas, the roughness on the welded joint surface were measured. The results were compared with those of the base material.

4. Results. Discussion

The experimental program demonstrated that the welding tools made of X38CrMoV5, WL20 and WT20 alloys, do not correspond to the heavy specific conditions from friction stir welding of steel. After 20 to 30 mm from the beginning of the effective welding process, the tool shoulder was heated excessively and became deformed, and pin presented an increased degree of wear (Figure 2).

Figure 2. Deformed shoulder of the welding tool, after 20-30 mm of weld.

As a result, the possibilities for manufacturing of welding tools using sintered tungsten carbide P20S, was analysed.

With this type of tools were developed two main experiments:

- experiment I: welding on one side, tool with smooth shoulder Ø = 20 mm and smooth tapered pin, with l_1 = 1.8 mm length;
- experiment II: welded on both sides, tool with smooth shoulder Ø = 20 mm and smooth tapered pin, with l_2 = 1.0 mm length.

The best results were obtained using welding parameters presented in Table 4.

Table 4. FSW process parameters- S420MC.

thicknes, s [mm]	Tool		
	Type pine - smooth conical	Pin length, l_{pin} [mm]	Shoulder diameter, $Ø_{shoulder}$ [mm]
2	welded on one side	1.8	20
	welded on both sides	1.0	20
	Welding process parameters		
	Rotational speed, n [rot/min]	Welding speed, v [mm/min]	Rotation direction
	800	20; 30; 40	counterclockwise
	800	30; 40	
	Pin axis position	On the joint line	

Experiment 1: Welding on one side

The aspect of friction stir welded joint on one side for S 420MC steel with s = 2 mm thick, using different welding speeds and increasing values, is shown in Figure 3.

The welding speed of 20 mm/min was used to start the process over a length of about 30÷40 mm, to protect the welding tool pin (to avoid shearing it to start moving the tool, when welding materials have not yet reached optimum temperature of plasticization).

The evolution of friction stir welding temperature on one side, using smooth tapered pin, recorded with thermographic camera, is shown in Figure 4.

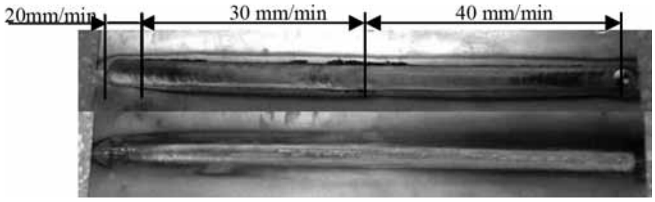

Figure 3. The aspect of welded joint on one side for S 420MC.

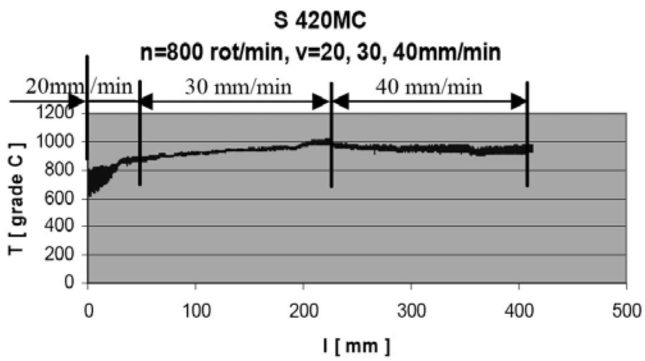

Figure 4. Temperature evolution recorded with thermographic camera.

Analyzing the evolution of temperature can be seen that:

- on the portion where speed v_1 = 20 mm/min was used, there is a high increase, in short time (1.5 ÷ 2 minutes), of the temperature to a value of approx. 880°C
- with increasing of welding speed value to v_2 = 30 mm/min (at the same rotational speed n = 800 rpm) the temperature continues to increase constantly, but slowly (with approx. 120°C within a time of approx. 6 minutes), reaching a maximum of approx. 1000°C, after 200 mm of weld. It can be seen that the process is stable and that there were no disturbances during the welding process on this portion.
- with increasing of the welding speed to v_3 = 40 mm/min, temperature showed a slightly downward trend, stabilizing at around 950°C.

Macroscopic analysis of welding on one side (Figure 5) demonstrates the absence of defects and good consolidation of the weld nugget.

Table 5 presents the results of structural examinations for S 420M.

Microstructures shown in Figure 6, for S420MC friction stir welded joint, are observed after attack by 2% Nital.

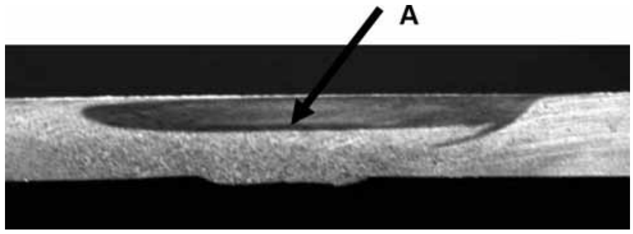

Figure 5. Macroscopic analysis of S420MC - friction stir welded on one side.

It was found that in the welded joint was obtained ferito-pearlitic structure, with a limited amount of perlite. With the introduction of large quantities of heat in the process, almost the entire microstructure is composed of equiaxed ferrite grains with a few large groups of pearlite that appear in well defined areas.

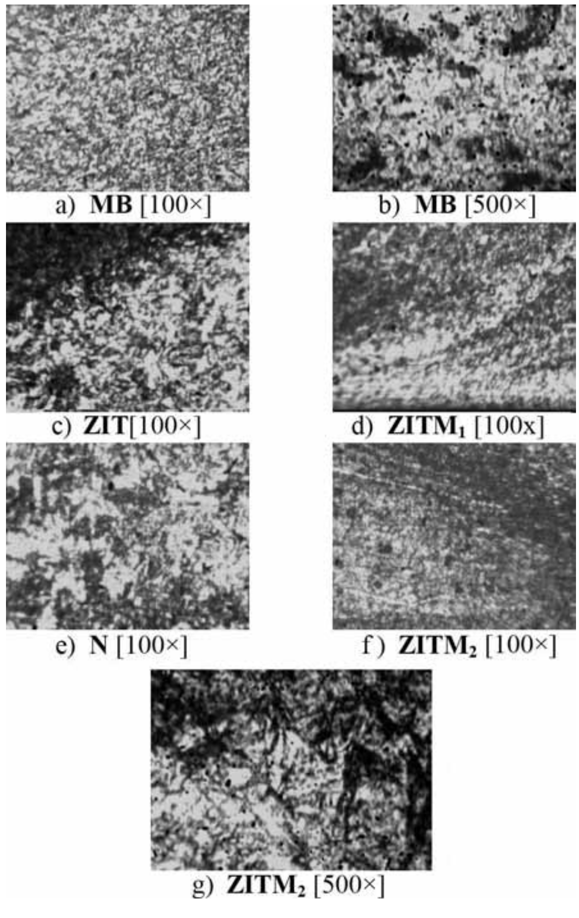

Figure 6. Microstructures in FSW joint for S 420MC.

Table 5. Results of structural examinations.

Marking sample	Microscopic examination [100x, 500x]			Areas investigated	Fig. no.
	Constituents SR 5000-97	Grain size SRI30 643:2003	Defects STAS 5500-74		
S420MC	Ferrite, pearlite, fine grain	~ 8	Are not observed	BM	6a, 6b
	Pearlite, ferrite, ferrite needle	6 - 7		HAZ	6c
	Pearlite, Bainite, martensite	-		$TMAZ_1$	6d
	Pearlite, ferrite, ferrite needle	4 - 5		N	6e
	Bainite, martensite and carbides	-		$TMAZ_2$	6f, 6g

Figure 7 presents the evolution of hardness for friction stir welded joint on one side, for steel S 420MC, measured in the transverse plane, on a line at 1 mm from the surface of the welded joint.

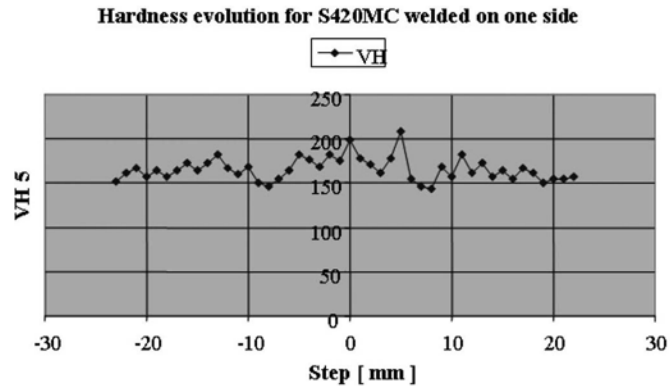

Figure 7. Hardness evolution for S420MC welded on one side.

In the HAZ and TMAZ values are close to those of the base metal and in the nugget they are about 10-20% higher than in BM.

Finishing grain is the major factor that contributes to hardening of the material in the nugget. The reason for obtaining a fine grain structure is the application of FSW procedure, which causes a major plastic deformation of the material.

Toward the welded joint surface, on ~ 1 mm depth, appear zone A (Figure 5), where the chemical composition analysis revealed the existence of elements W (max. 1.42%) and Ti (max. 0.14%). This is due to excessive wear of the welding tool shoulder.

The sample was taken after 200 mm from the beginning of the welding process, when the tool temperature was approx. 1000°C.

Experiment II: Welding on both sides

The aspect of friction stir welded joint for S 420MC steel, having s = 2 mm thickness, welded to the second part, using different welding speeds (30mm/min respectively 40 mm/min) and 800 rpm rotational speed is shown in Figure 8.

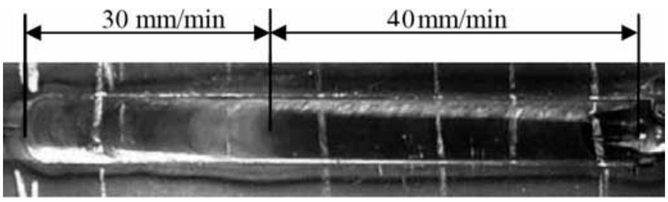

Figure 8. Joint aspect for S 420MC welded on both sides.

The temperature evolution to friction stir welding on both sides using smooth conical pin having l_2=1.0 mm length, recorded by thermographic camera, is presented in Figure 9.

It is noted that unlike experiment I, temperatures developed are generally less and this because the pin of the welding tool has a smaller volume by about 50% and therefore a small friction surface with welding material.

The temperature increase until a maximum value of approx. 880-900 °C, then begins to decrease with increasing of the welding speed, stabilized at an average value of approx. 670 °C.

The macroscopic analysis for friction stir welding on both sides is shown in Figure 10.

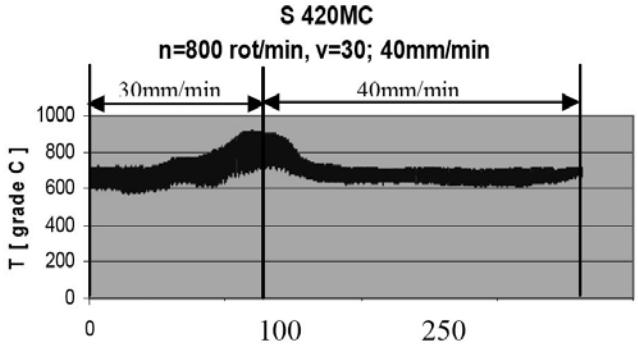

Figure 9. Evolution of temperature monitorized by thermographic camera.

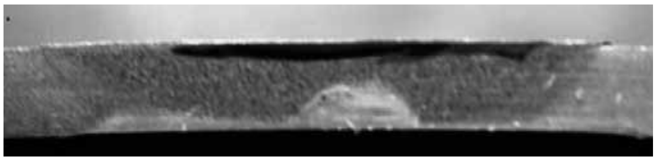

Figure 10. Macroscopic analysis for friction stir welding on both sides - S420MC.

It can be observed how the welded joint was made, without defects or imperfections.

To the welding of thin sheet steel (s ≤ 2 mm), an important factor is represented by geometry and dimensions of the welding tool shoulder, its influence during the process on a max.1mm deep (on both sides approx. 2 mm) from the weld surface was felt. This makes that the geometry and the pin dimensions in this case (stopping plate s ≈ 2 mm) are no longer the determining factor to obtaining FSW joints without defects/ imperfections.

The hardness evolution for friction stir welded joint on both sides for steel S 420MC is shown in Figure 11.

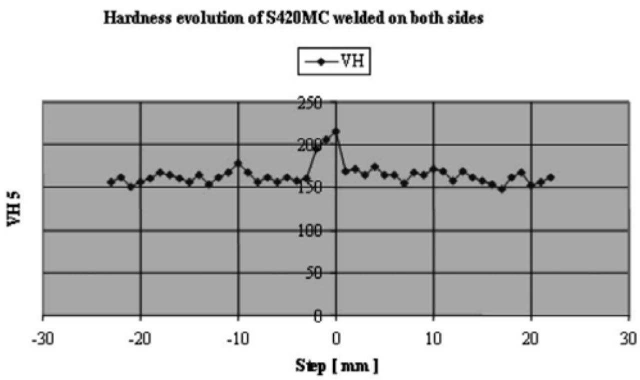

Figure 11. Hardness evolution for friction stir welded joint on both sides of steel S 420MC.

The hardness of the material are comparable to that of base metal, in all FSW specific areas of welded joints, except the nugget, on the part corresponding to the retreating side of the welding tool, where they are higher by approx.30%.

The explanation for this is similar to that in experiment I.

In figures 12 and 13 samples of FSW welded on one side, respectively on both sides, are presented after static tensile test.

It is noted that the welding on one side, some samples were broken in the base metal at ca. 40mm from joint line.

At welding on both sides, the sample taken to 50 mm from the beginning of process, has broken in the base metal and the sample taken to 150 mm from the beginning of process has broken in the HAZ, in range of the maximum diameter of the material welding tool shoulder.

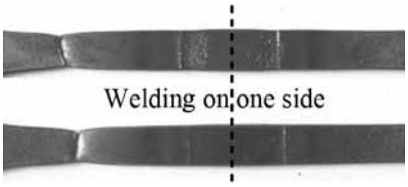

Figure 12. Aspects of FSW welded samples, on one side, after static tensile test.

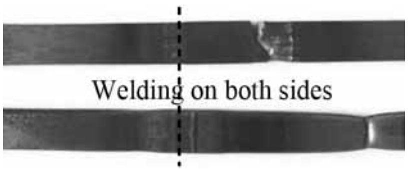

Figure 13. Aspects of FSW welded samples, on both sides, after static tensile test.

Tensile strength in this case represented 98.3% of the tensile strength of the base metal.

Static bending test results revealed that the welded joints have maximum degree of deformation, for welding on one side and welding on both sides.

The results of experimental program showed that S 420MC steel can be welded by FSW, welded joint characteristics are compatible with those of the base metal.

5. Conclusions

- FSW process is applicable with very good results to welding steel S 420MC, in terms of optimized welding parameters.
- in terms of mechanical characteristics of welding joint is recommended that welding be done, if possible, on one side;
- welding tools made of high alloy steel and hardened to 52- 56 HRC, used to joining of lightweight materials and tools made of some W alloys, can not be used to friction stir welding of steel;
- welding tools made of W sintered carbide can be used to develop research programs and demonstration of FSW quality to S 420MC, but are not a solution for industrial application due to reduced lifetime (high degree of wear).
- it has demonstrated that application of FSW to weld low carbon steels, finishing grain in nugget is obtained, similarly to aluminum alloys. Also complex phase transformations occurring during FSW process and mechanical properties were improved compared with the base metal (especially to welding on one side).

References

[1]. Fuller, C.B., Friction Stir Tooling: Tool Materials and Designs, Friction Stir Welding and Processing, pag.7-37, ASM International, 2007

[2]. Duborg,L., Dacheux, P., Design and properties of FSW tools: a literature review, The 6h International Friction Stir Welding Symposium, Saint- Sauveur, Montreal, Canada, 10-13 Oct.2006

[3]. Ueji,R., Fujii, H., Cui, L., Nishioka,A., Kunishige,K., Nogi, K., Mater. Sci. Eng. A 423 (2006) 324.

[4]. Fujii, H., Cui, L., Maeda, M., Nogi, K., Mater. Sci. Eng. A 419 (2006) 25

[5]. Sato, Y.S., Muraguchi, M., Kokawa, H., Microstructure and properties of FS welded 304 stainless steel using W-based alloy tool, Friction Stir Welding and Processing IV, 2007, p.261-268

[6]. Proiect Nucleu „Dezvoltarea procedeului de sudare FSW pentru imbinarea materialelor metalice cu rezistenta mecanica §i duritate mare", ISIM Timişoara, PN 09160104/2009-2010

[7]. Boțilă, L., Cojocaru,R., Safta, V. , Comportarea la sudare prin frecare cu element activ rotitor a titanului Ti Gr 2, Revista BID - ISIM, Nr. 4/2008.

[8]. Safta, V., Aplicarea termografiei in infraro§u la controlul nedistructiv al imbinarilor sudate prin frecare cu element activ rotitor, Revista BID - ISIM, Nr. 1/2010.