MICROSTRUCTURE AND MECHANICAL PROPERTIES OF FRICTION STIR WELDED AlMg4.5Mn ALLOY

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Abstract: *A comprehensive research of Friction Stir Welding of 4 mm thick sheet aluminium alloy (AlMg4.5Mn) for forming was done. A vast variety of process parameters was tested according to the plan of experiments at constant 2° tilt angle. Specially designed tensile test specimens were sectioned perpendicularly to the welding direction. The microstructure was prepared for the observation on a light microscope under the polarized light source. Vickers micro-hardness was measured. The results show the influence of FSW process parameters on the formation of the microstructure and mechanical properties.*

Keywords:
– friction stir welding
– AlMg4.5Mn
– welding parameters
– mechanical properties
– weld failures

1. INTRODUCTION

Friction stir welding (FSW) has now become an important process in the joining of aluminium alloys (AA) and other materials which are soft in relation to the material used as the tool for stirring the metal. Since there is no macroscopic melting involved, the controls needed in fusion welding to avoid phenomena such as solidification and liquation cracking, porosity, and loss of volatile solutes can be avoided. These recognized advantages of solid-state joining have led to attempts to use FSW for a wide range of alloys. After the invention at TWI in 1991 R&D in FSW, associated technologies have mushroomed. By the end of 2007, TWI had issued 200 licenses for the use of the process, and 2630 patent applications had been filed relating to FSW by the end of 2010 [1-3].

The process of FSW has a few variants: beside classical FSW there are, also, friction stir spot welding (FSSW), friction stir shoulder welding (FSShW) and friction stir processing (FSP). FSSW is useful for joining materials in spots where there is no need for sealed joint and where the loading forces are smaller. It represents an alternative to resistance spot welding where the actual cost of making a spot weld in the automobile industry is a few cents of a dollar [4]. With this cost, FSSW must compete unless there are particular difficulties with welding of special materials or special combinations of materials. FSShW was developed as an alternative to FSW in order to minimize the tool costs. At FSW tool, the weakest element of the tool is its pin, which dictates the tool lifetime. By eliminating the pin from the tool, the tool life can be significantly extended. But with the FSShW only smaller depths of welds (up to 3 mm) can be produced in AA. FSP is very similar to FSW although it is not used for welding but for crushing the material grains in very small grains in order to get the superplastic properties of the AA[5-8].

The research explored the weldability of 4 mm thick sheet aluminium alloy (AlMg4, 5Mn, Al 5083) in the butt joint. We developed a FSW tool for welding of 4 mm thick sheets. We pursue the influence of welding parameters on the stability of welding defects in the weld, the microstructure and mechanical properties. The results showed that the welding parameters exert a noticeable effect on the microstructure, welding defects and weld mechanical properties. When welding thin sheet metal in one step, it is necessary to pay attention to the width of the gap since a big gap has a negative influence on the formation of a good weld.

2. EXPERIMENTAL

2.1. Dimensions and composition of workpieces

The workpiece dimensions were 180 x 60 x 4 mm and were made of AlMg4.5Mn. The chemical composition of this alloy is 4.35 wt. % Mg, 0.42 wt. % Mn, 0.12 wt. % Si, 0.087 wt. % Cr, 0.29 wt. % Fe, 0.019 wt. % Zn, 0.013 wt. % Ti and the rest Al [9]. Some physical and mechanical properties of this aluminium alloy are presented in Table 1.

2.2. FSW tool

The FSW tool was made of EN 42CrMo4 steel, with chemical composition 0.41 wt. % C, 0.2 wt. % Si, 0.75 wt. % Mn, 1.05 wt. % Cr, 0.23 wt. % Mo and the rest Fe [10]. Figure 1 shows the FSW tool geometry. The FSW tool consists of treaded pin 3.9 mm high and the concave shoulder for producing pressure under the tool. Right upon the shoulder, 4 grooves were made in order to effectively cool the tool with the compressed air.

2.3. Friction stir welding

A vast plan of experiments was prepared regarding the universal milling machine (Prvomajska ALG 100E) capabilities. A plan was prepared to test different combinations of tool rotations and FSW speeds at the constant tilt angle of 2°. The FSW tool rotated from 200 to 1250 rpm, and the welding speeds changed from 71 to 450 mm/min. Both the factor of feed per revolution (FPR) in µm/revolution and the revolution per feed (RPF) in revolutions/mm were introduced so as to better distinguish among different welding parameters. The FPR varied from 56 to 1400 µm/rev. A backing plate underneath the workpiece prevented aluminium alloy to flow away from the seam. The two workpieces were clamped in a vice.

2.4. Preparation of testing samples and testing

From the produced welds, a miniature sample for a tensile test and a sample for the analysis of the microstructure were prepared.
The sample for tensile test is shown in Fig. 2. A sample was sectioned perpendicularly to the welding direction in order to get the whole heat affected zone (HAZ) into the sample. Before sectioning the samples with water jet from the weld, the workpiece surfaces were milled.

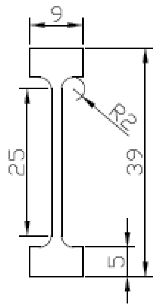

Figure 2. Drawings of miniature tensile test samples

Table 1. Physical and mechanical properties of AlMg4.5Mn. [9]

Property	ρ [kg/m^3]	R_m [MPa]	$R_{p0.2}$ [MPa]	E[GPa]	Tsol [˚C]	Tliq [˚C]
AlMg4.5Mn	2.660	275 - 300	125 - 149	71	580	640

Figure 1 a) FSW tool geometry and b) experimental FSW.

The tensile tests were done using computer controlled Zwick/Roell Z050 tensile testing machine. Measurements were done using Testexpert software. At shorter samples, the strain was measured incrementally through the axis and at longer samples with an extensometer directly on the sample.

The analysis samples of the microstructure were sectioned, ground and polished. They were etched using Keller reagent (2% NHO_3, 1% HCl, 1% HF and 9% H_2O). The microstructure was analyzed using a light optic microscope with the digital camera to acquire digital images. Vickers micro-hardness was measured.

3. RESULTS AND DISCUSSION

3.1. Visual assessment of FSW welds

Figure 3 shows a top view of the FSW welds. The end of the weld is indicated with a small hole – a negative of the FSW tool pin. The majority of welds is of good quality and has smooth weld apices, due to a good forming capability of the tested AlMg4.5Mn alloy. At sample 3, a pin of the FSW tool broke during the welding. After the tool got broken, a small crack appeared at the weld surface due to the lack of material. The weld surface becomes rougher due to the change in the tool shape. A pin brake appeared due to big FPR (2250 μm/rev), which resulted in lower weld temperature and higher welding forces.

At sample 7, the FPR was 56.8 μm/rev i.e. a tool moved for a ~ 0.05 mm per tool revolution. This means that not only the heat input but also the weld temperature was high. Due to these conditions, a FSW tool moved more into the material resulting in a burr beside the weld.

The comparison of samples 10, 11 and 12 is shown in Fig. 4. These samples were made with different gap widths. The weld apices are smooth at samples with gaps up to 0.5 mm width. Welding joints with the gap wider than 0.75 mm are not appropriate for FSW welding.

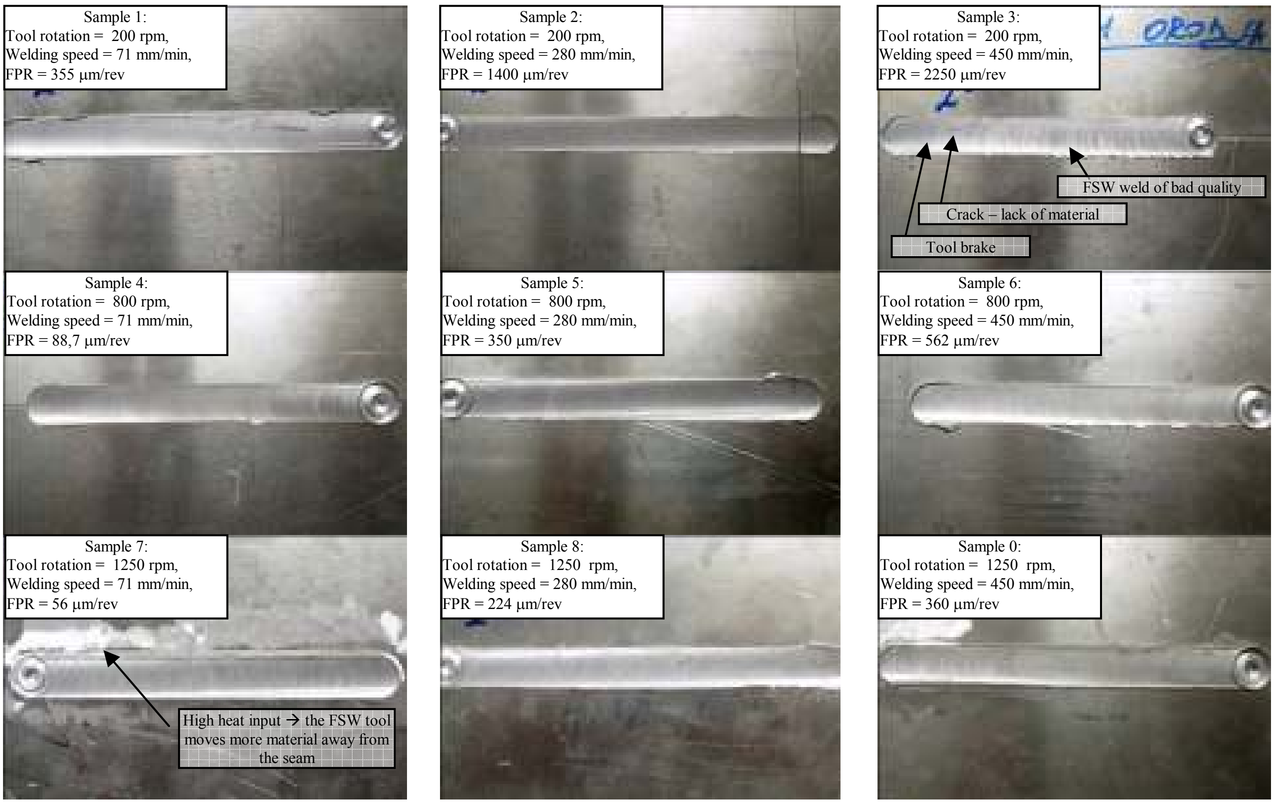

Figure 3. A top view on the weld.

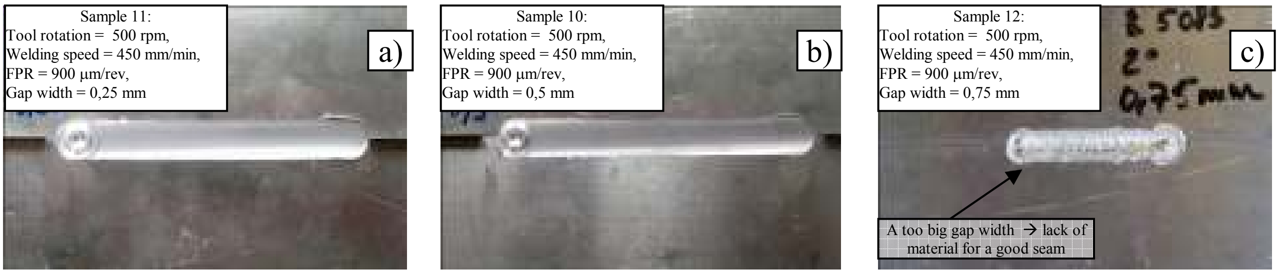

Figure 4. The influence of gap width: a) 0.25 mm, b) 0.5 mm and c) 0.75 mm.

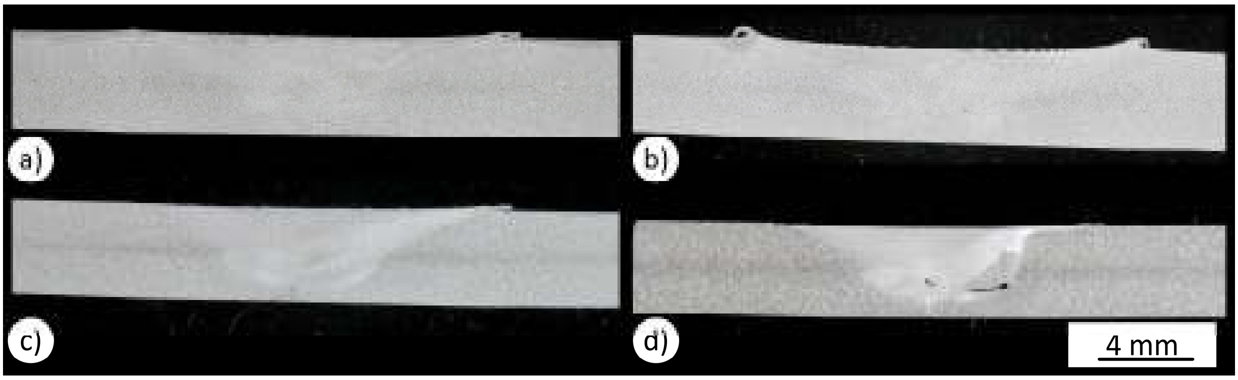

Figure 5. Macrostructure of FSW welds: a) sample 5 (800 rpm, 350 mm/min), b) sample 0 (1250 rpm, 360 mm/min), c) sample 11 (500 rpm, 900 mm/min) and d) sample 3 (200 rpm, 2250 mm/min).

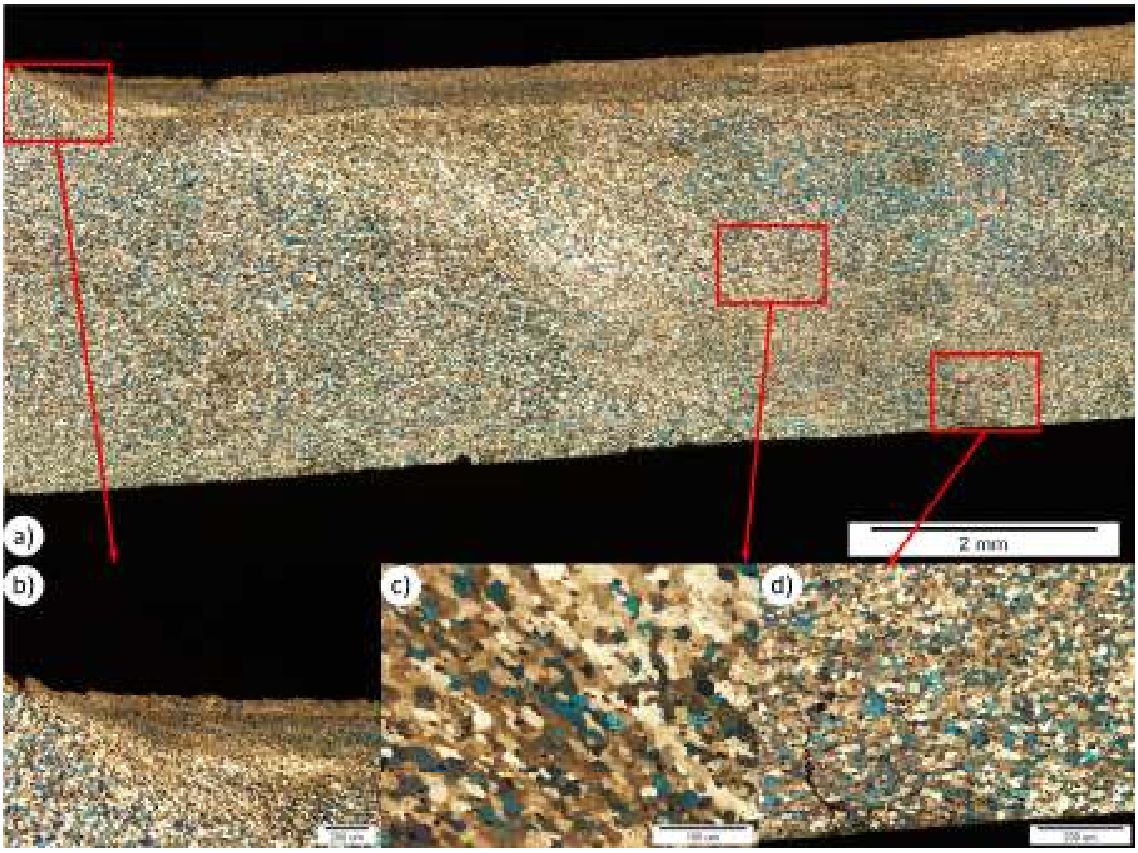

Figure 6. Microstructure of FSW weld produced at 1250 rpm and 56.8 mm/min: a) automated stitched image acquisition, b) microstructure under tool shoulder and the base metal, c) weld microstructure and d) weld root with oxide line and insufficient material stirring.

3.2. Weld microstructure

Figure 5 shows macrostructures of FSW welds. Figures 5a, 5b and 5c show quality friction stir weld produced at FPR 350 mm/min, 360 mm/min and 900 mm/min. In all of these cases a good mixing of materials was achieved, even though the FSW welding parameters were different. A minor lack of joining is present at the root of the sample 11 (Fig. 5c), due to insufficient penetration of FSW tool into the material and the presence of aluminium oxide. In Figures 5a-c a small toe flash is visible,due to the selected tilt angle and tool position. In Fig. 5b a slight underfill is evident, as a consequence of tool position regarding the base metal.

At weld macrosections shown in Fig. 5d, a so called "*worm hole*" or "*tunneling*" defect is present. The reason for "*worm hole"* appearance is insufficient penetration of FSW tool into the material i.e. in low welding force in tool axis, which prevented accumulation of pressure under the tool. Another reason for the "*worm hole*" appearance could be also too large FPR, which did not produce enough heat input for welding.

Figure 6 shows the microstructure of the weld produced at 1250 rpm and 56.8 mm/min. Figure 6a presents the automated stitched image. In this figure a finer weld microstructure can be noticed in the FSW weld, especially immediately underneath the tool shoulder if compared with the base metal (Fig. 6b). An approx. 10 μm is the grain size in the weld as shown in the Fig. 6c. The weld root is insufficiently stirred due to slightly too small tool pin height (Fig. 6d).

3.3. Hardness

The microhardness across the weld and HAZ was approximately 80 HV and was slightly higher than the microhardness of the base metal 78 HV. No significant difference in hardness across the weld and HAZ was noted except for the sample 3, which was welded with the lowest frictional heat input FPR 2250 μm/rev. Weld microhardness at this sample was 105 HV. A reason for higher hardness is in deformation strengthening of the weld due to low heat input.

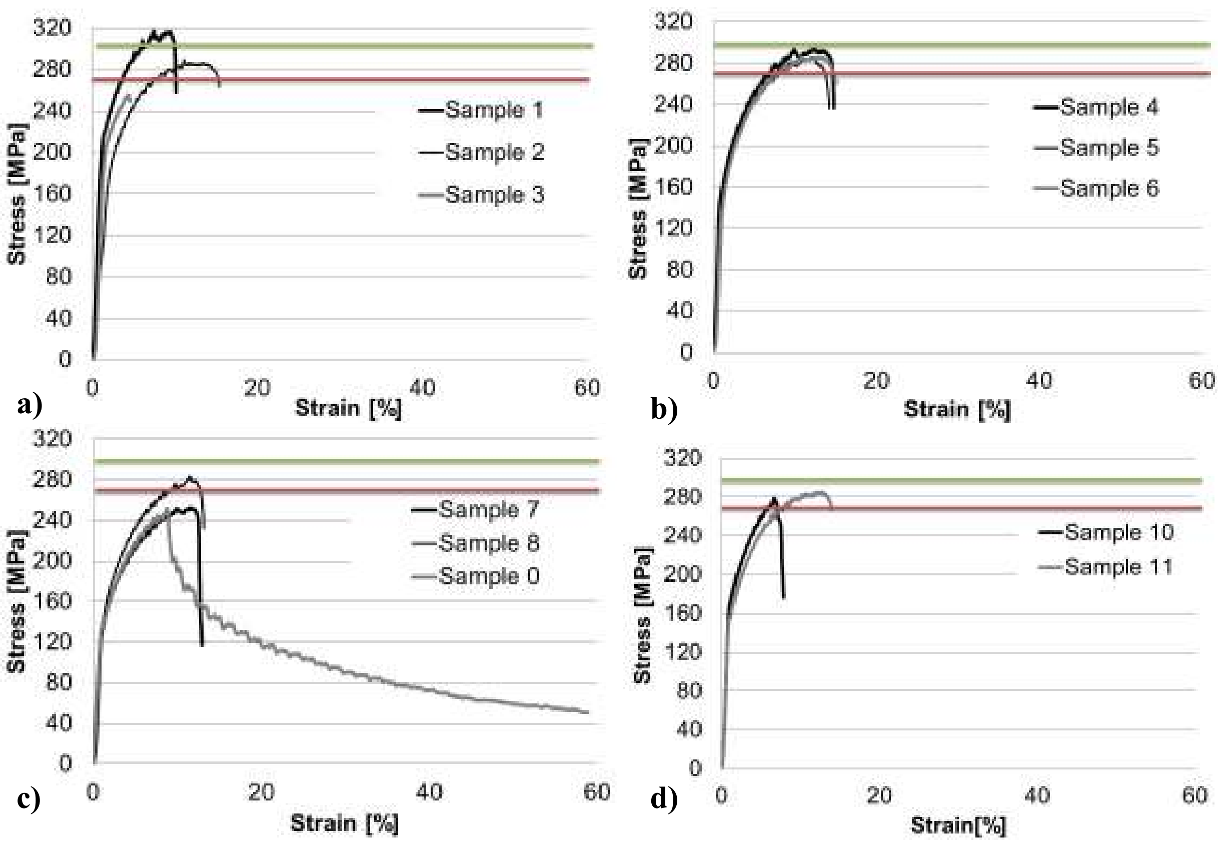

Figure 7. Tensile strength perpendicular to the welding direction.

3.4. Tensile strength

Yield strength of AlMg4.5Mn aluminium alloy is between 125 and 149 MPa and ultimate tensile strength between 275 and 300 MPa (Tab. 1) [9]. Tensile test samples were cut out perpendicularly to the weld length. Due to the use of non-standard test specimens, the results could hardly be compared with the results from the literature. The ultimate tensile strength at longer tensile test specimens was generally in the range for the base aluminium alloy. When welding with the 200 rpm and welding speed of 71 mm/min the tensile strength was even higher i.e. 320 MPa. The tensile strength of the base metal was not measured, but taken from the literature data.

A smallest scatter was obtained when welding with 800 rpm (samples 4, 5 and 6) and 500 rpm (samples 10 and 11) (Fig. 7b and d). The reason for that is probably in tool rotating speed and FPR in the range 88 and 562 µm/rev. A small scatter was also obtained at samples welded at tool rotation of 1250 rpm, where FPR was in the range between 56 and 900 µm/rev. The ultimate tensile strength was lower than at tool rotation of 800 rpm, probably due to the higher tool rotation speed of 1250 rpm (Fig. 8c). The highest scatter of tensile strength was obtained at welding with tool rotation of 200 rpm. The reason for higher scatter was the extreme FPR in the range between 355 and 2250 µm/rev. At samples 2 and 3 the FPR was 1400 and 2250 µm/rev, which is too high since the tensile strength is decreasing with the increasing FPR. The highest tensile strength was found at FPR 355 µm/rev. The optimal value of FPR regarding our results is in the range between 50 and 1000 (1400) µm/rev.

4. CONCLUSIONS

A FSW tool was developed for FSW, with which good and repeatable welds were produced. A visual assessment of tool apices and tool roots enable us to distinguish between good and inappropriate weld. A good FSW welds have smooth apices and filled weld root, while the weld surface is slightly sunk (~ 0.2 mm). When FSW tool was welding approximately 0.2 mm under the workpiece surface, a welding force in the z-direction i.e. material pressure under the FSW tool was big enough to produce good welds without "worm hole" defects. When the FPR was in the reasonable range between 50 and 1000 µm/rev, enough frictional energy was generated for producing welds of good quality. In the case where FPR was extremely high (2250 µm/rev), the welding forces were so high that the pin from tool broke.

5. LIST OF SYMBOLS

feed per rate	*FPR*,	m/rev
tensile strength	R_m,	MPa
yield strength	$R_{p0,2}$,	MPa
modulus of elasticity	E,	GPa
densty	ρ,	kg/m^3
solidus temperature	Tsol,	˚C
liquidus temperature	Tliq,	˚C

REFERENCES

[1] Threadgill, P.L. et al.: *Friction stir welding of aluminium alloys,* International Materials Reviews, 54 (2009) 49-93.
[2] Bhadeshia, H.K.D.H., *Editorial*, Science and Technology of Welding & Joining, 15 (2010) 646-7.
[3] DebRoy, T. et al.: *Friction stir welding of dissimilar alloys – a perspective*, Science and Technology of Welding & Joining, 15 (2010) 266-70.
[4] Bhadeshia, H.K.D.H., et al.: *Critical assessment: friction stir welding of steels,* Science and Technology of Welding & Joining. 14 (2009) 193-6.
[5] Fingerman, S.: *Friction stir welding and processing*, Sci-Tech News, 61 (2007) 77-.
[6] Mishra, R. et al.: *Friction stir welding and processing*, Materials Science and Engineering R: Reports, 50 (2005) 1-78.
[7] Srinagesh, K.: *Friction stir welding and processing. Choice*, Current Reviews for Academic Libraries, 46 (2008) 332-.
[8] Genevois, C. et al.: *Comparative study on local and global mechanical properties of 2024 T351, 2024 T6 and 5251 O friction stir welds*, Materials Science and Engineering A, 415 (2006) 162–170.
[9] http://aluminium.matter.org.uk/aluselect/03_physical_browse.asp, 17.5.2011
[10] http://www.metalravne.com/selector/steels/vcmo140.html, 17.5.2011

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