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FRICTION STIR WELDING (FSW) OF ALUMINIUM FOAM SANDWICH PANELS

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The article focuses on the influence of welding speed and tool tilt angle upon the mechanical properties at the friction stir welding of aluminium foam sandwich panels. Double side welding was used for producing butt welds of aluminium sandwich panels applying insertion of extruded aluminium profile. Such insertion provided lower pressure of the tool upon the aluminium panels, providing also sufficient volume of the material required for the weldment formation. Ultimate tensile strength and flexural strength for three-point bending test have been determined for samples taken from the welded joints. Results have confirmed anticipated effects of independent variables.

Key words: friction stir welding, aluminium foam, welding speed, sandwich panels, tool tilt angle

INTRODUCTION

Aluminium foam sandwich (AFS) panels are sheet-shaped structures comprising two layers of aluminium sheets and a core of aluminium foam in between giving the structure a high degree of stiffness. The specific properties of aluminium foams are low material density, high material stiffness, good impact resistance, high energy absorption, fire resistance and thermal insulation [1-3]. The face sheets of AFS bear tensile and compression forces from bending loads; the core layer, in turn, contrasts shear and compressive loads [4]. A large thickness core layer increases the sandwich's moment of inertia at low weight increment and supports the face sheets against buckling.

Light-weight construction based on AFS panels largely depends on efficient joining techniques. Extra critical issues must be taken into account: a) cell integrity and/or foam stability, b) different melting points of foam and cover sheet. By applying any joining technology joining only involves the region close to the cover sheets while the two foam edges remain separated [5].

The difference in density between foam and skin limits the execution of welds through the thickness. Tungsten inert gas (TIG) welding, Metal inert gas (MIG) welding and laser welding were shown to be suitable techniques for joining AFS panels but any attempt of increasing the welding power density results in severe damage of the foam [5, 6]. Since Friction Stir Welding (FSW) is a solid - state welding process with low heat input suitable for welding of aluminium alloys it could also be appropriate for welding AFS panels. The main problem to utilize FSW for welding AFS panels is the low indentation resistance of the foam core [6]. When the tool pin is inserted between two adjacent coversheets the material is partially pressured into the pores below the pin and the frictional forces enabling good stirring and thus metallurgical bonding do not come up. Consequently some kind of support should be inserted between coversheets prior to FSW to provide stable base for a rotating tool. If the welding will be performed properly the supporting profiles will be welded to both adjacent coversheets in single operation.

FSW process parameters include tool rotation speed, welding speed, tool geometry, tool tilt angle, axial force of the tool and type of welding joint. This investigation has a focus on the FSW tool design, tool movement and orientation in the process of welding AFS panels.

MATERIAL PROPERTIES

AFS panels used for this experiment are made of 1 mm thick EN AW-6082 T4 aluminium alloy cover sheets and AlMg3Si6 aluminium foam core. Thickness of these panels is 12 ± 0,5 mm. In the production phase the foamable precursor material was bonded with aluminium sheets by roll bonding without any adhesives. Dimensions, mechanical and chemical properties of the panels were investigated before welding. Using a digital calliper panel thickness and pore diameter were measured. Average pore thickness is = 3,172 mm. Average panel thickness is 12,5 mm. Using a top loading balancer mass of specimens was measured and relative density = 0,194 is calculated. Young's modulus and shear modulus were calculated according to the literature [3]. Young's modulus of the foam is E_p = 4,887 GPa. Shear modulus of the foam is G_p = 1,833 GPa.

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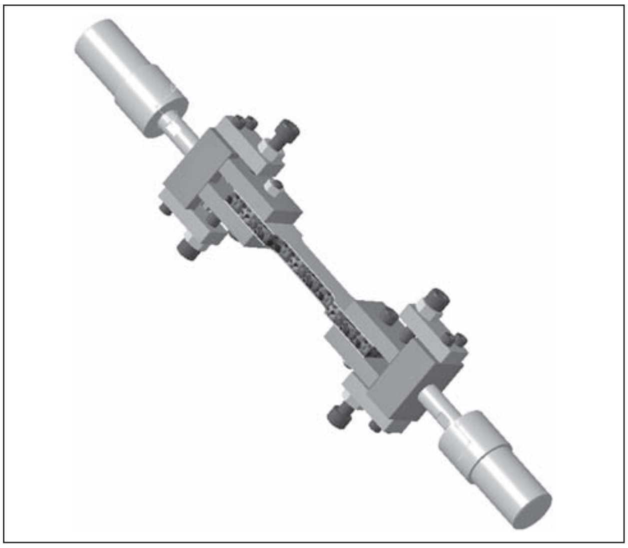

Figure 1 Clamping device for uniaxial tensile testing

Specimens for uniaxial compression testing were sectioned from AFS panels in dimensions according to ASTM C365-03 [7]. Average compressive stress has been calculated to be = 5,28 MPa when deformation reaches 0,7 mm. Three point bending test was performed according to ASTM C393-00 [8]. Average longitudinal bending stresses in the cover sheets is calculated to be = 129,26 MPa.

Figure 1 shows specially designed clamping device used for uniaxial tensile testing. The purpose of this device was to avoid undesirable deformation of the specimens which can be result of low compression resistance in the head of the specimen. Average ultimate tensile strength for AFS panel has been calculated to be = 27,68 MPa.

Quantitative material characterization was performed with handheld Olympus XRF X-ray Fluorescence analyzer. The measurement has confirmed that chemical composition of AFS cover sheets alloy according to standard EN 573-3:2014 matches the aluminium alloy EN AW-6082 [9].

EXPERIMENTAL WORK

Universal milling machine Prvomajska ALG 200B was used for FSW. According to the designed factorial planning variable parameters were welding speed (23, 58 and 93 mm/min) and tool tilt angle (2°, 3° and 4°). The tool rotation speed was constantly 1900 min^{-1}. Double side welding was used for producing butt welds of AFS panels applying insertion of homogenous aluminium extruded section. This solid insert was extruded aluminium alloy EN AW-6060 T66 with cross section dimensions 14 × 3 mm.

Applying iteration approach, welding tool has been designed. After welding with a specific tool, specimens for macroanalysis were sectioned from the produced weld (Figure 2). If specimen had contained imperfections the tool design had been modified to eliminate the cause of the imperfections. Figure 3 shows the final welding tool. The welding tool was made from X38CrMoV51 tool steel, quenched and tempered to get the surface hardness of 50 HRC [10].

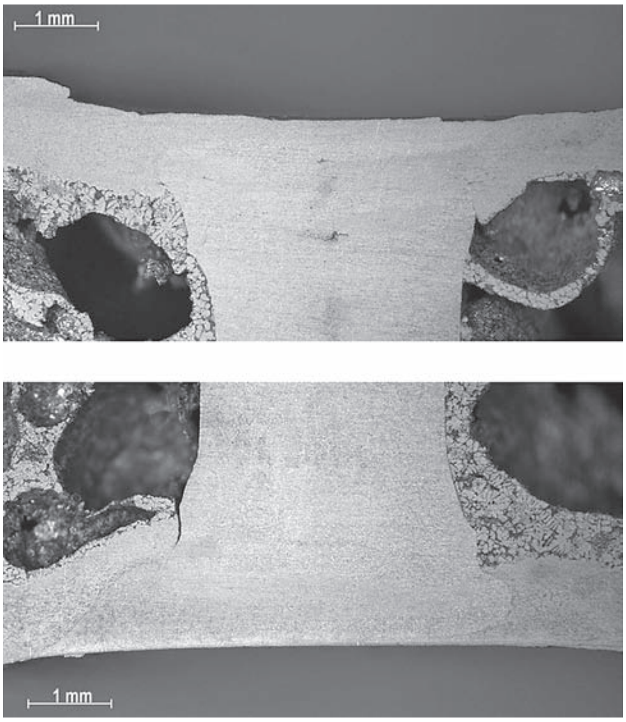

Figure 2 Macroanalysis of the welded joint

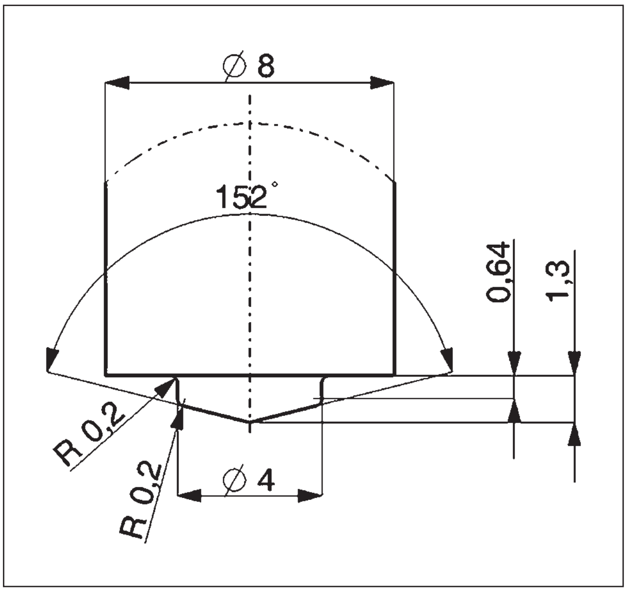

Figure 3 Final design of the FSW tool pin

The welding has been executed with different welding parameters according the 3-level factorial design planning containing 13 states of experiment. Levels of welding speed were: 23, 58 and 93 mm/min. Levels of tool tilt angle were 2°, 3° and 4°.

The workpieces were clamped in a specially created clamping device placed on the dynamometer. Welding was done along the rolling direction of the cover sheets. The axial force of the tool wasn't a controlled parameter because welding machine hasn't got a force control option.

During the welding the downward force of the tool was measured with 3-component dynamometer KISTLER, type 9257A. Signals were processed applying National Instruments Signal Express 2013 software. Produced welds have been accepted if the tool pressure during the welding was below the specified limit. The limit was defined by uniaxial compression testing of the AFS panels. The limiting level of the axial force was specified to be F_N = 5 524,6 N.

From each produced weld two specimens for tensile strength testing and two specimens for 3 point bend testing had been sectioned perpendicular to the welding direction with a band saw.

RESULTS AND DISSCUSION

Measurement of the forces acting from the tool on the welding material has shown that the downward force was well below the limiting level for all states of the experiment. At the beginning of the process the downward force achieved a value between 1,3 and 2,3 kN. When the tool pin has reached plunging depth the downward force reduced to approximately 700 kN and stayed stable with slighter oscillations depending on the structure of the aluminium foam in the aluminium sandwich panels and also on the tool shoulder diameter.

The uniaxial tensile testing of the specimens was conducted on a servo-hydraulic testing machine VEB Werkstoffprüfmaschinen GmbH, EU 40 mod. The load was applied at a constant speed of 10 mm/min. Measurement was done using TIRAtest System software. The average value of the maximal tensile force for the specific welded joint $\overline{F}_m$ was calculated from the two measured values of maximal tensile force F_m for specimens produced from the same welded joint. Using obtained value ultimate tensile strength $\overline{R}_m$ has been calculated.

Although the welding and the specimens were not in accordance with EN ISO 25239-4:2012, which refers only for homogeneous materials, the measured values could be compared with conformance levels. The ultimate tensile strength of welded test specimen in the post-welded condition shall be at least 70 % of the ultimate tensile strength of the parent material [11]. This refers only for butt joints of heat treatable aluminium alloys produced with FSW. With reference to the ultimate tensile strength of the parent material is $\overline{R}_m$ = 27,68 MPa all of the welds with ultimate tensile strength above 19,376 MPa could be accepted.

The three-point bend testing of welded test specimens was conducted on the same servo hydraulic testing machine as for the uniaxial tensile testing. The load was applied at a constant speed of 8 mm/min. Average value of the maximal flexural force for the specific weld $\overline{F}_f$ was calculated from the two measured values of maximal flexural force F_f for specimens sectioned from the same weld. Measured values of maximal flexural force F_m for all specimens made with welding speed v = 58 mm/min and tool tilt angle α = 3° are above the average value of maximal flexural force of AFS panels which is $\overline{R}_{\text{ms om}}$ 1 321,8 N. Using the obtained value, the flexural strength R_{ms} was calculated.

The results of the experiment were analyzed and statistically processed using Design Expert 6.0.5 software. Using a Response Surface Methodology a mathematical model for prediction of ultimate tensile strength R_m and flexural strength R_{ms} in the welded joints of AFS panels has been established.

For the prediction of tensile strength a reduced quadratic mathematical model has been established:

$$R_m = 7{,}208 + 0{,}204 \times v + 2{,}004 \times \alpha - 0{,}001 \times v^2 - 0{,}016\, v \times \alpha \;/\; \text{MPa}$$

Figure 4 presents the response surface for the ultimate tensile strength mathematic model. Analysis of variance – ANOVA for this model has been generated. The model F-value of 19,35 imply that model is significant. There is only a 0,04% chance that an F-value of this magnitude could occur due to the noise. The „R-Squared“ value is 0,9063. The „Pred R-Squared“ of 0,8109 is in reasonable agreement with the „Adj R-Squared“ of 0,8595 which indicates a good adequacy of the reduced quadratic model with model terms welding speed (v), tool tilt angle (α), square of welding speed (v^2) and product of welding speed and tool tilt angle (v × α).

For the prediction of flexural strength a reduced quadratic model has been established:

$$R_{ms} = 45{,}224 + 1{,}445 \times v + 15{,}453 \times \alpha - 0{,}012 \times v^2 \;/\; \text{MPa}$$

Figure 5 presents the response surface for the flexural strength mathematic model.

Analysis of Variance – ANOVA for this defines the model F-value of 13,37. There is only a 0,11% chance that an F-value of this magnitude could occur due to the noise. The „R-Squared“ value is 0,8168. The „Pred R-Squared“ of 0,6766 is in reasonable agreement with the

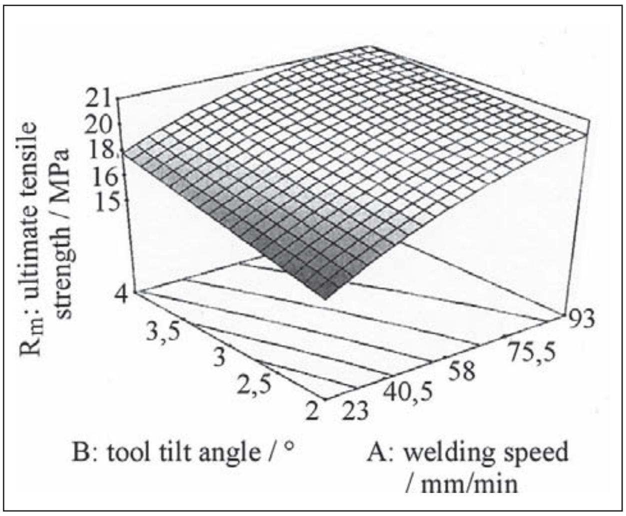

Figure 4 The influence of welding parameters on the ultimate tensile strength

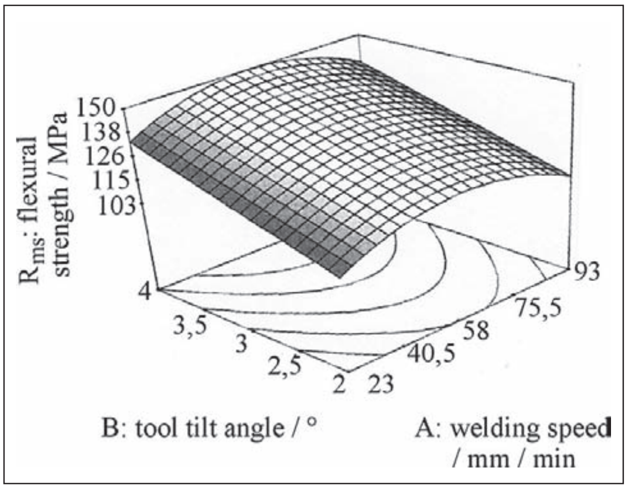

Figure 5 The influence of welding parameters on flexural strength

„Adj R-Squared“ of 0,7557 which indicates a good adequacy of the reduced quadratic model with model terms welding speed (v), tool tilt angle (α) and square of welding speed (v^2).

CONCLUSIONS

Visual inspection of the welds has confirmed that increase in welding speed results in higher roughness of the weld face. Tool tilt angle has no influence on the appearance of the weld face.

Measurement of the forces during the welding process has confirmed that tool pressure can be below the compression strength of aluminium foam in the core.

Tensile strength testing and flexural strength testing results differ for every state of the experiment. It can be concluded that welding speed and tool tilt angle have significant influence on tensile strength and flexural strength of welded joints. Using a Response Surface Methodology a mathematical model for prediction of tensile strength and flexural strength in the welded joints of aluminium sandwich panels has been established. According to the mathematical models variation of the tool tilt angle has the highest influence both on the ultimate tensile strength and the flexural strength of the welded joints.

The coefficients of determining the ultimate tensile strength model and flexural strength model are in compliance with the heterogeneity of mechanical properties of AFS panels.

Regarding the obtained results, it can be concluded that friction stir welding of aluminium foam sandwich panels in butt-weld configuration, applying insertion of homogenous aluminium extruded section, with a proper tool design and defined welding parameters can provide welded joints of outer sheets with acceptable mechanical properties.

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Note: The responsible translator for English language is Andreas Mihaljinec, Bedekovčina, Croatia (Metafrasi d.o.o.)