In-Process Tool Rotational Speed Variation with Constant Heat Input in Friction Stir Welding of AZ31 Sheets with Variable Thickness

Gianluca Buffa�1, a), Davide Campanella�1, b), Archimede Forcellese2, c), Livan Fratini1, d) and Michela Simoncini3, e)

1University of Palermo, Dept. of Chemical, Management, Computer Science and Mechanical Engineering, Palermo, Italy
2Università Politecnica delle Marche, DIISM, Via Brecce Bianche, 60121 Ancona, Italy.
3Università degli Studi eCampus, via Isimbardi 10, 22060 Novedrate (CO), Italy.

a)Corresponding author: gianluca.buffa@unipa.it
b)davide.campanella@unipa.it
c)a.forcellese@univpm.it
d)livan.fratini@unipa.it
e)michela.simoncini@uniecampus.it

Abstract. In the present work, friction stir welding experiments on AZ31 magnesium alloy sheets, characterized by a variable thickness along the welding line, were carried out. The approach adapted during welding consisted in maintaining constant the heat input to the joint. To this purpose, the rotational speed of the pin tool was increased with decreasing thickness and decreased with increasing thickness in order to obtain the same temperatures during welding. The amount by which the rotational speed was changed as a function of the sheet thickness was defined on the basis of the results given by FEM simulations of the FSW process. Finally, the effect of the in-process variation of the tool rotational speed on the mechanical and microstructural properties of FSWed joints was analysed by comparing both the nominal stress vs. nominal strain curves and microstructure of FSWed joints obtained in different process conditions. It was observed that FSW performed by keeping constant the heat input to the joint leads to almost coincident results both in terms of the curve shape, ultimate tensile strength and ultimate elongation values, and microstructure.

INTRODUCTION

Recent efforts of ground transportation, aeronautics, aerospace and naval industries are addressed to weight reduction. The pursue of this goal can result in several advantages, in terms of reduced costs of raw material and reduced fuel consumption of the final product, with consequent reduction of the environmental impact of the whole production chain. The use of tailored blanks, i.e. blanks of different material and/or thickness, allows for efficient use of material only where it is “needed” and, hence, final component weight reduction.

As far as sheet metals are regarded, a few different strategies can be followed, e.g. tailored blanks (different materials or thickness), tailored heat treated blanks (different material properties within the same component) and Tailored Rolled Blanks (TRB). In particular, the latter have been encountering a growing interest by both industry and academia. Ryabkov at al.[1] showed the feasibility of producing 3D TRBs characterized by both longitudinal and latitudinal thickness change, by a combination of Flexible Rolling and Strip Profile Rolling. Meyer at al.[2] demonstrated the possibility to increase the maximum drawing depth and, at the same time, reducing the final component weight, by properly using TRBs. Finally, Kleiner at al.[3], in a comprehensive survey on the different strategies to produce and use light structures, highlighted that the combined use of TRB sand subsequent joining can results in the production of weight and load optimized complex parts.
Among the processes which can be used to weld TRBs of light alloys, Friction Stir Welding (FSW) appears as on
the most promising because of its capability to weld traditionally considered “non weldable” materials with excellent
joint resistance. In FSW, a rotating tool is inserted into the sheets to be welded and moved along the weld seam with
constant speed. The tool is made by a pin, which is inserted in the sheets and a shoulder, which produces most of the
heat by friction on the top surface of the sheets. As a solid state welding process, the typical defects of both traditional
and innovative welding techniques, e.g. inclusions, porosities, cracks and distortions, can be avoided or severely
limited. FSW can be successfully applied to magnesium alloys. The effect of the process parameters and sheet
thickness on the mechanical and microstructural properties, and post-welding formability of FSWed joints in
magnesium alloy were widely investigated, and the process parameters leading to sound joints were defined [4, 5].

FSW has been demonstrated suitable to produce Tailored Welded Blanks (TWBs). Buffa et al.[6] successfully
applied FSW to the production of TWBs obtained welding two AA7075 sheets of different thickness. Silva et al.
[7] investigated the formability by Single Point Incremental Forming of TWBs obtained by FSW of two AA1050-
H111 sheets with thickness equal to 1.5mm and 2mm. Finally, Sheikh et al.[8] studied the influence of the process
parameters and tool dimension on the micro and macro mechanical properties of TWB obtained joining two AA6181-
T4 sheets, 1mm and 2mm in thickness, respectively. Weld efficiency equal or higher than 90% was obtained thus
demonstrating the feasibility of the process.

In a previous work, the authors demonstrated that FSW can be used to successfully join sheets in AZ31 magnesium
alloy characterized by variable thickness along the welding line[9]. Two different approaches aiming at maintaining
the vertical tool force constant during the welding stage, based on the in-process variation of the tool rotational speed
or tool plunging, were developed. In particular, with the former approach, as the sheet thickness increases, the vertical
force increases but the simultaneous increase in the rotational speed makes the material softening more pronounced
allowing to keep constant the value of the vertical force. The opposite behavior was observed as the sheet thickness
decreases. Although this approach resulted in sound welds, the microstructural properties change along the weld line
as a function of the sheet thickness due to the variation of the heat input to the joint as the tool rotational speed changes
resulting in non-uniform mechanical properties of the weld.

In the present work, FSW of AZ31 sheets, characterized by a different thicknesses along the welding line, were
performed by adopting an approach consisting in keeping constant the heat input to the joint during the experiments.
To this purpose, the rotational speed was increased with decreasing thickness and decreased with increasing thickness.
The amount by which increasing or decreasing the rotational speed as a function of the sheet thickness was defined
on the base of the results given by a dedicated numerical model of the FSW process. The influence of the in-process
variation of the tool rotational speed on the mechanical properties and microstructure of joints was discussed.

**EXPERIMENTS AND NUMERICAL MODELING**

**Friction stir welding experiments**

Butt joints in AZ31 magnesium alloy were obtained by means of FSW operations. The base material was
characterized by values of the ultimate tensile strength (UTS) and ultimate elongation (UE) equal to 250 MPa and
11.2%, respectively. The sheets were cut into blanks, 180 mm in length and 80 mm in width, and then FSWed with
the welding line perpendicular to the rolling direction. Before welding, the sheets were machined to create zones with
different thicknesses along the welding line (Fig. 1). In particular, the initial thickness, equal to 2.5 mm, was decreased
by milling sheets up to 2 mm leaving a hump, 0.1 mm in height and 30 mm in length (Fig. 1a), or a dip, 0.05 mm in
depth and 30 mm in length (Fig. 1b), in the central zone of the blanks along the welding line.

Experiments were carried out by equipping a machining center with an adaptive control constraint (ACC) system
that allows to adjust the rotational speed (ω) with the aim to keep constant the heat input to the joint during the welding
stage of the process. The plunging stage was performed with lowering and rotational speed values equal to 1.5 mm/min
and 1500 rpm, respectively, until the plunging depth of 0.1 mm was reached. The welding stage started on the 2 mm
thick sheet, with ω=1500 rpm and welding speed (v) equal to 60 mm/min. Such values were obtained by analyzing
the results shown in a previous paper in which the effect of welding parameters on the vertical force during FSW of
AZ31 alloy was investigated[7]. The heat input corresponding to such condition was taken as the target value to be
maintained constant during the entire welding stage. As the sheet thickness varied, the ω value was adjusted to
maintain unchanged the heat input to the joint on the basis of the results obtained by the dedicated FEM model of the
FSW process described in the next section. In particular, as the zone with a dip of 0.05 mm in depth was welded, the
rotational speed was increased from 1500 to 2000 rpm whilst, as the region with a hump of 0.1 mm in height was
welded, the \( \omega \) value was decreased from 1500 to 1200 rpm. Finally, as the pin tool in its movement along the welding line passes the dip or hump, the rotational speed backs to its initial value of 1500 rpm corresponding to the sheet thickness of 2 mm.

A rotating pin tool in H13 tool steel, with a shoulder diameter of 12 mm, a cone base diameter of 3.5 mm, a cone height of 1.7 mm, and a pin angle equal to 30°, was used. In all FSW trials the tool displacement was equal to 160 mm and the tilt angle was 2°. For each testing condition, at least three FSW repetitions were performed.

![FIGURE 1. Welded blanks with zones at different thicknesses along the welding line: (a) sheet with a hump zone and (b) sheet with a dip zone.](image)

**Finite element method analysis**

A fully 3D FEM model for the FSW process of magnesium alloys, that is thermo-mechanically coupled and with rigid visco-plastic material behavior, was developed by the authors [10] on the basis of the acquired know-how on FSW of aluminum alloys. The workpiece was modelled as a rigid visco-plastic material, whilst the welding tool is assumed as rigid. Figure 2 shows the meshed sheets at the beginning of the simulation. A constant thermal conductivity of 96 W/m °K and a specific heat capacity of 1 J/g °C, taken from literature for magnesium alloys, were used. A rigid visco-plastic temperature and strain rate dependent material model, obtained by processing the experimental flow curves at high temperatures, was used. A constant interface heat exchange coefficient of 11 [N/(mm s °C)] was assumed for the tool sheet contact surface. The workpiece modeling was performed using a “single block” continuum model (sheet blank without a gap) in order to avoid the instabilities due to the intermittent contact at the sheet-sheet and sheet-tool interfaces. The sheet blank was meshed with 30,000 tetrahedral elements with minimum single edges of about 0.4 mm. A non-uniform mesh with adaptive re-meshing was adopted with smaller elements close to the tool and a re-meshing referring volume was identified all along the tool feed movement. Finally, a constant shear friction factor of 0.18 was used for tool-sheet interface on the basis of a preliminary numerical campaign. Three different conditions were modelled, with sheet thicknesses of 2, 2.10 and 1.95 mm. The tool height at the end of the plunging stage was fixed in order to have a clearance of 0.2 mm between the tool pin bottom and the bottom surface of the sheet. In this way, different plunge values were obtained for the two sets of simulation. Fig. 2 shows the meshed model at the end of the plunge phase in the 2 mm sheets. For each set, different simulations were run with varying tool rotational speed in the range of 1000÷2000 rpm, with steps of 100 rpm, and constant welding speed of 60 mm/min. The predicted temperature distributions were compared to the reference condition characterized by a sheet thickness of 2 mm and a rotational speed equal to 1500 rpm. The latter configuration, which was selected based on a preliminary experimental campaign [13], resulted in a sound joint with proper microstructure.

**Uniaxial tensile testing**

The mechanical properties of the FSWed joints were evaluated by means of room temperature uniaxial tensile tests carried out using a servo-hydraulic universal testing machine. Specimens with the loading direction perpendicular to the welding line were machined from the welded blanks so that the gauge length, equal to the shoulder mark, was obtained into the dip or hump zones. The tests were performed according to ASTM E8/E8M and BS EN 895. The results were plotted as nominal stress (s) vs. nominal strain (e) curves by which the values of the ultimate tensile
strength (UTS) and ultimate elongation in percentage (UE) were derived. At least three tests were performed for each testing condition.

**FIGURE 2.** Sketch of the developed model after the plunge phase completion.

**Light optical microscopy**

Microstructure of the AZ31 FSWed joints was widely investigated by means of the light optical microscopy. The alloy was etched using acetic-picral (10 ml acetic acid, 4.2 g picric acid, 10 ml H$_2$O, 70 ml ethanol (95%)). The overview of the cross section of the joint and the details of the different zones (nugget, thermo-mechanically affected and heat affected zones) were acquired. The microstructural analysis was performed at different depths from the top to the bottom surface of the sheet, in close proximity to the weld axis and both in the advancing and retreating side.

**RESULTS**

The rotational speed values assigned to the pin tool in order to perform the friction stir welding of AZ31 magnesium alloy with constant heat input to the weld, irrespective of the sheet thickness, was defined by means of FEM simulations of the process. To this purpose, the heat input corresponding to the rotational speed of 1500 rpm, welding speed equal to 60 mm/min and tool plunging of 0.1 (with sheet thickness of 2 mm), was taken as the target value (reference condition) to be maintained constant during the entire welding stage. Two different sets of numerical simulations were run in order to identify the $\omega$ values allowing to maintain constant the heat input, i.e. temperature into the welded zone, during the welding stage of the process performed on sheets with different thicknesses. Figure 3 shows the top view of the temperature distribution as the sheet thickness is equal to 2 mm, 1.95 mm (dip zone) and 2.10 mm (hump zone), with $\omega$ values equal to 1500 rpm, 2000 rpm and 1200 rpm, respectively.

**FIGURE 3.** Top view of the temperature distribution after FSW with a welding length of 30 mm: (a) reference condition - $\omega$=1500 rpm (thickness of 2 mm), (b) dip (thickness of 1.95 mm) - $\omega$=2000 rpm, (c) hump (thickness of 2.10 mm) - $\omega$=1200 rpm.
It is seen that very similar temperatures are obtained as a distance of 30 mm is weld, i.e. the process already reached the steady state. The rotational speed values selected on the basis of the FEM results were used to perform FSW processes on AZ31 magnesium sheets characterized by zones with different sheet thicknesses.

The mechanical properties of the joints, obtained by adjusting the $\omega$ value during FSW in order to keep the heat input to the weld constant, were investigated by means of the uniaxial tensile tests performed on specimens, with the loading direction perpendicular to the welding line, obtained both in the dip and hump zones of the FSWed blanks. The nominal stress vs. nominal strain curves (Fig. 4) show that, by applying the approach proposed in this work, the UTS and UE exhibited by the FSWed joints in the dip zone with $\omega = 2000$ rpm, equal to 187 MPa and 3.95%, respectively, are almost coincident with the ones in the hump zone with $\omega = 1200$ rpm, equal to 190 MPa and 4.1%, respectively. Furthermore, by comparing the stress – strain curves with the one of the weld in the reference condition ($\omega = 1200$ rpm and sheet thickness of 2 mm), negligible differences can be observed, both in terms of the curve shape and UTS and UE values. Also the microstructural analysis shows very similar results in the different experimental conditions investigated. As a matter of fact, by considering the nugget region of the joints obtained in the reference condition (Fig. 5a) and in the hump and dip zones (Fig.s 5b and 5c), it can be seen that size and distribution of grains are almost coincident.

The results, in terms of mechanical properties and microstructure, can be attributed to the very similar heat input to the joint during the welding stage, obtained by means of the adjustment of the $\omega$ value as a function of the sheet thickness given by the FEM model of the FSW process. Such results demonstrated that the proposed approach can be effectively used to produce sound FSWed joints with constant mechanical properties notwithstanding the thickness variation.

**FIGURE 4.** Typical nominal stress vs. nominal strain curves obtained by welded blanks with a dip, a hump and zone along the welding line obtained by adjusting the rotational speed during FSW.

**FIGURE 5.** Microstructure of the nugget zone of the: (a) reference condition ($\omega=1500$ rpm), (b) dip ($\omega=2000$ rpm) and (c) hump ($\omega=1200$ rpm).
CONCLUSIONS

An innovative approach to the friction stir welding, based on an in-process variation of the tool rotational speed to maintain a constant heat input during the welding stage of sheets with variable thickness, was proposed. To this purpose, the rotational speed values as a function of the sheet thickness were defined on the basis of the results obtained by a dedicated FEM model of the FSW of AZ31 blanks. Then, FSW experiments on sheets characterized by the presence of a dip or a hump along the welding line were performed by adjusting the rotational speed during the welding stage. In particular, the rotational speed was increased from 1500 to 2000 rpm as the zone with a dip of 0.05 mm in depth was welded, whilst it was decreased from 1500 to 1200 rpm as the region with a hump of 0.1 mm in height was welded.

It was observed that the mechanical properties, in terms of ultimate tensile strength and ultimate elongation, and microstructure exhibited by the FSWed joints in the dip zone ($\omega = 2000$ rpm, sheet thickness of 1.95 mm) are very similar to the ones in the hump zone ($\omega = 1200$ rpm, sheet thickness of 2.10 mm); furthermore, by comparing the nominal stress vs. nominal strain curves with the one obtained in the reference condition ($\omega = 1500$ rpm, sheet thickness of 2 mm), negligible discrepancies can be observed, both in terms of the curve shape and ultimate tensile strength and elongation values. Such behaviour can be attributed to the constant heat input to the joint during the welding stage obtained by means of the adjustment of the rotational speed value as a function of the sheet thickness given by the FEM simulations of the FSW process.

ACKNOWLEDGMENTS

The authors wish to thank Dr. M. Pieralisi and Mr. D. Ciccarelli for their help in carrying out the experimental tests.

REFERENCES