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Experimental and Numerical Analysis on Post Welding Formability of FSWed AZ31 Magnesium Alloy Thin Joints obtained using a “Pinless” Tool Configuration

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Abstract. The post welding formability of friction stir welded AZ31 magnesium alloy thin sheets (1.5 mm thick), obtained using a “pinless” tool configuration, was widely investigated by means of the hemispherical punch method at 350°C, with a constant crosshead speed of 0.1 mm/s. The results were compared with those obtained on the base material. It has shown that formability of the joints is lower than the one of the base material. The experimental work was supported by a numerical investigation based on FEM in order to highlight the material flow occurring during the welding process. Additionally, hemispherical punch tests were simulated starting from the calculated conditions, in terms of accumulated strain, derived from the simulation of the welding process. Good agreement was found between the experimental and the numerical results, both for the welding and post welding forming.

Keywords: Magnesium alloy, Thin sheets, Friction stir welding, Pinless tool configuration, Post welding formability, FEM

1. INTRODUCTION

Nowadays, an urgent and remarkable issue in manufacturing is the environmental sustainability and the main targets are related to more efficient use of materials and energy. Environmental requirements are mainly considered as an inevitable “must” [1, 2].

In sheet metal forming processes, the necessity to design sustainable products offers many opportunities, such as selection of “environmental-friendly” materials, waste minimisation, energy efficiency, end-of life strategies, etc. In particular, the automotive industry felt the effects of problems related to the gases emissions and their environmental influences. The main contribution that can be given in order to reduce fuel consumption and exhaust emission levels is related to mass reduction [3]. To this purpose, in the latest years, much attention was paid to lightweight materials that can offer great potentialities in vehicles weight reduction due to their low densities. Among them, magnesium (Mg) alloys are very attractive due the high strength to weight ratio [4]. In turn, such materials are often “difficult” to be welded or even “non-weldable” as the conventional fusion welding of magnesium alloys often produces porosity in the weld joint, which deteriorates its mechanical properties. To solve this problem, friction stir welding (FSW) represents a very attractive welding technology that can be successfully used in joining materials difficult to be welded with the traditional fusion techniques, such as Mg alloys [5].

Several scientific studies on FSW of magnesium alloys have been performed in order to investigate the influence of the most relevant process parameters and of tool geometry on the material flow and weld quality. Most of them deal with thicknesses of the welded joints varying between 3 and 6 mm, whilst only few investigations were focused on the FSW of thin sheets, less than 2 mm thick because, as sheet thickness decreases, the production of FSWed joints becomes ever more complex [6]. In order to overcome such difficulties, the FSW can be performed using a “pinless” tool configuration, characterized by the lack of the pin, in which the heat flux during process is generated only by the frictional force at the tool shoulder–workpiece interface [7].

Since magnesium alloys exhibit a very poor formability at room temperature due to their hcp structure, the post-welding formability of FSWed joints in these alloys have to be investigated under warm forming conditions, so that formability improves as the process temperature increases, owing to the activation of further sliding planes [8].

In this framework, the present investigation aims at studying the warm formability of FSWed AZ31 magnesium alloy thin sheets obtained using a “pinless” tool configuration. A preliminary investigation performed by the authors has allowed defining the welding parameters at which the FSW process produces joints with the highest micro- and macro-mechanical properties [7]. Then, the formability of FSWed blanks was evaluated in terms of forming limit curves (FLCs), obtained using the hemispherical punch method. The results were compared with those obtained, under the same experimental conditions, on the base material (BM). The experimental work was supported by a numerical investigation based on finite element method (FEM) in order to highlight the material flow occurring during the welding process. Additionally, hemispherical punch tests were simulated starting from the calculated conditions, in terms of accumulated strain, derived from the simulation of the welding process. Good agreement was found between the experimental and the numerical results; in this way the formability of the obtained joints can be successfully predicted and the numerical model can be used as a powerful design tool for the whole production cycle of the joints (welding and post welding forming).

2. EXPERIMENTAL AND NUMERICAL PROCEDURES

2.1. Friction stir welding experiments

Friction stir welding of thin sheets in AZ31 magnesium alloy, with a thickness of 1.5 mm, was carried out in a CNC machining center using a tooling in H13 tool steel, characterised by a “pinless” tool configuration with a shoulder diameter of 19 mm. The welding operations were carried out using a nuting angle of 2° on blanks 180 mm in length and 80 mm in width. The welding line was perpendicular to the rolling direction.

In a previous paper [7], the authors have shown that both ultimate tensile strength (UTS) and ultimate elongation (UE), evaluated on FSWed joints at room temperature, rise with increasing the ratio between rotational speed (ω) and welding speed (v) up to a maximum and then decrease as ω/v further increases (figure 1). The highest mechanical properties of the welded joints were obtained in the range of ω/v ratio varying from 50 to 70 rev/mm. For this reason, in the present work the post-welding formability was evaluated on samples obtained from FSW performed using a rotational speed equal to 2500 rpm and a welding speed of 50 mm/min (ω/v = 50 rev/mm).

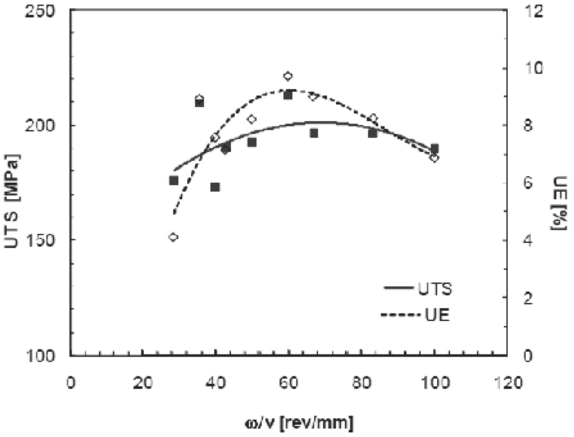

Figure 1. Ultimate tensile strength and ultimate elongation values at room temperature of FSWed joints, as a function of the rotational/welding speed ratio.

2.2. Hemispherical punch tests

Formability of base alloy and FSWed joints in AZ31 magnesium alloy sheet, expressed in terms of forming limit curves, was investigated at constant temperature of 350°C, using the hemispherical punch test [8], with a constant crosshead speed of 0.1 mm/s. In particular, samples characterised by length to width ratios varying from 1 (100 mm x 100 mm) to 8 (12.5 mm x 100 mm) were used. For each specimen geometry of the base alloy, the length side was parallel to the rolling direction. The hemispherical punch tests were performed until the onset of necking. At least three repetitions for each process condition were carried out.

In order to determine the strain distribution after testing, the surface of each sheet sample was meshed using a regular line grid with 1.5 mm in line distance. An accurate image analysis system was used to evaluate the major (ε_1) and minor (ε_2) strains.

2.3. Numerical analysis

Two different numerical models were set up. The first FEM model was developed for the FSW process of thin sheets in Mg alloy, with the pinless tool configuration. In order to develop the 3D, thermo-mechanically coupled, lagrangian model, the DEFROM3D^{tm} commercial software was utilized. A rigid viscoplastic material model, depending on the local values of strain, strain rate and temperature, was adopted [9]. The sheets to be welded were modelled as a “single block”; in other words no actual welding occurs and the tool during its movement induces the material flow as in friction stir processing. It has already been demonstrated by the authors that this approach produces the same distributions of the main field variables of the actual FSW process [10]. The initial phases of the process, namely the tool sinking, was simulated in order to obtain the temperature distribution needed for the beginning of the actual welding stage. The sheet was modelled through about 25,000 tetrahedral elements and a remeshing referring volume was identified along the welding line. In this area a finer mesh, characterized by an average dimension of 0.35 mm, was utilized in order to have about 4 elements along the sheet thickness. The tool was modelled as rigid body and meshed, for the thermal analysis, with about 8,000 tetrahedral elements. Other fixture parts have been modelled through proper boundary conditions. As far as the thermal analysis is concerned, constant thermal conductivity k=96 [W/m °K] and specific heat capacity c=1 [J/g °C], taken from literature for magnesium alloys, have been utilized. A constant interface heat exchange coefficient of 11 [N/(mm s °C)] was utilized for the tool sheet contact surface. Finally, a constant shear friction factor of 0.18 is used for tool-sheet interface on the basis of previous numerical campaign [9]. Figure 2 shows a sketch of the developed model.

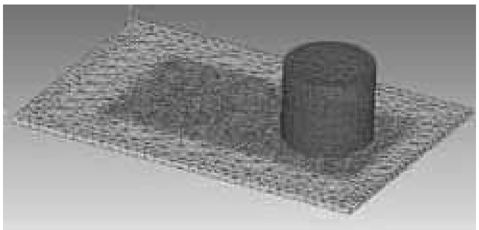

Figure 2. Sketch of the model for FSW process of thin AZ31 Mg sheets, with the pinless tool configuration.

As far as the simulation of the hemispherical punch test is regarded, a 3D isothermal analysis was performed using the same simulation software utilized for the FSW process. The punch and the die were modelled as rigid bodies while the blankholder was modelled through proper boundary conditions. In this way just the circular area of the blank involved in the deformation process was modelled obtaining faster computational times. A plane of symmetry, perpendicular to the welding line, was introduced in order to limit the computational cost of the simulations. A remeshing referring volume was identified around the tool and a finer mesh, with average element size equal to 0.2 mm, was selected for this area. In this way a total of about 34,000 tetrahedral elements were obtained, it should be observed that a finer mesh, with respect to the one used for the FSW process is required in the deformation area to correctly predict the strain and stress distributions during the forming process. In order to take into account the effect of the welding process on the forming tests, the distribution of accumulated strain was imported, through an interpolation procedure, in the new mesh and geometry of the blank before the beginning of the forming stage simulation.

Figure 3 shows the model sketch and the utilized mesh for the specimen characterised by length to width ratio equal to 1; highlighted dots on the lateral surface of the sheet indicate the blocked nodes simulating the effects of the blankholder.

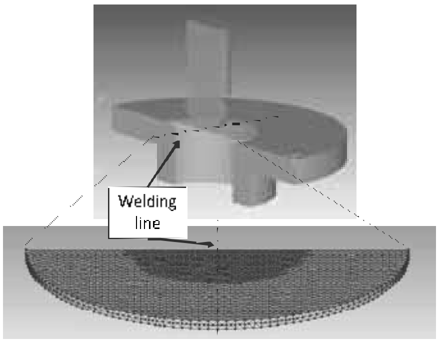

Figure 3. Sketch of the model for hemispherical punch test of BM and FSWed joints.

3. RESULTS AND DISCUSSION

As shown in a previous paper [11], on the basis of the results obtained with tensile tests, that showed an improvement in ductility and a decrease in flow stress with increasing temperature and decreasing strain rate, the formability of the FSWed joint and BM was analysed in terms of the forming limit curves obtained at temperature of 350°C and punch speed equal to 0.1 mm/s (corresponding to strain rate values ranging from 10^{-3} to 10^{-2} s^{-1}).

The forming limit curves of the base material and welded joint, obtained by means of the hemispherical punch test, are shown in figure 4. It can be observed that the formability of AZ31 base alloy exhibits the typical behaviour shown on the same alloy, but with different sheet thicknesses, in previous works of the authors under the same experimental conditions [8, 12]. In particular, the formability, defined as the safe area below the FLC, is much higher in the drawing side of the FLD than that in the stretching region.

The comparison between the FLC of the BM and that obtained by the FSWed joint, under the same experimental conditions, shows a strong reduction in the welded joint formability. To this purpose, figure 5 shows square samples subjected to the hemispherical punch test at 350°C and 0.1 mm/s. The BM shows a dome height at the onset of necking higher than that obtained by the FSWed joint. Such behaviour, consistent with that observed by the authors in [8], is more marked in the drawing side of forming limit diagram, in which very low values of minor and major strains were measured; this means that the welded joint exhibits a low attitude to be formed as the loading direction is perpendicular to the welding line. The occurrence of biaxial stretching improves the formability of the FSWed joints mainly in terms of minor strain limit value in comparison with that observed in the drawing side.

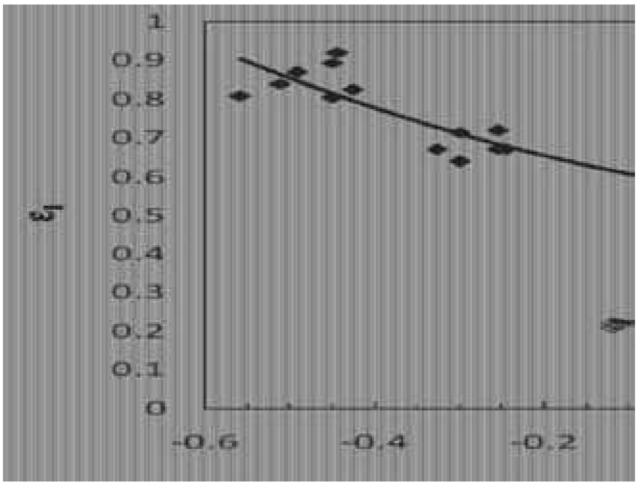

Figure 4. Forming limit curves of BM and FSWed joint.

Figure 5. Comparison between BM and FSWed square samples subjected to the hemispherical punch test (350°C; 0.1 mm/s).

The FEM model was utilized in order to explain the above described behaviour. First, the simulation of the FSW process was developed. figure 6 shows a 3D view of the temperature distributions after the process reached its steady state.

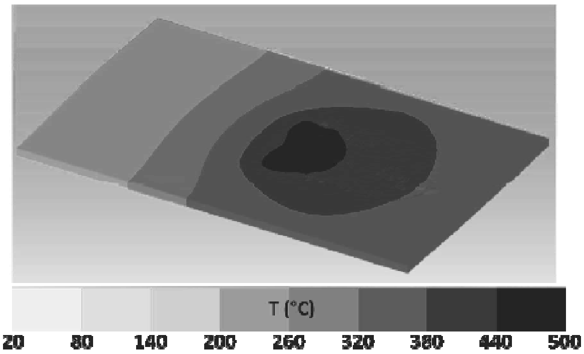

Figure 6. 3D view of the temperature distribution during the process.

As it can be seen quite large temperature values are observed. This is due to the large shoulder diameter with respect to the thickness of the sheets and to the large rotational speed used. Due to the absence of a tool pin, higher temperatures are needed in order to reach the required material mixing resulting in a sound joint. As anticipated in the previous paragraph, the accumulated strain distribution obtained after the simulation of the welding process was interpolated into the mesh of the circular sheet used for the simulation of the forming process. Figure 7 shows the above described strain distribution in the blank ready for the hemispherical punch test.

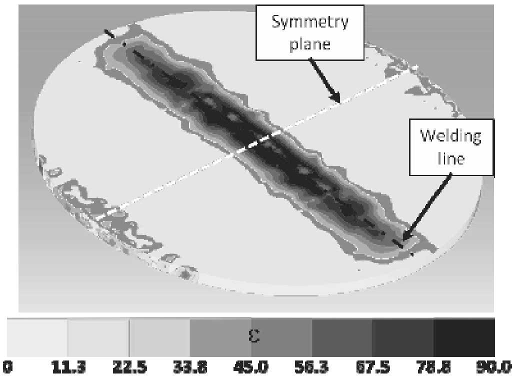

Figure 7. Calculated strain distribution in the "as welded" sheet at the beginning of the forming stage.

The extremely large deformation values calculated are due to the combination of the operative parameters selected. It has been demonstrated that in FSW strain increases with increasing rotational speed and with decreasing advancing speed [10]. As a matter of fact the considered case study is characterized by fast rotational speed, i.e. 2500 rpm, and slow feed rate, i.e. 50 mm/min, thus resulting in maximum accumulated strain values of about 90. Finally, the Von Mises stress distribution is shown for a dome height correspondent to a safe condition for both the base material and the friction stir welded blank (figure 8).

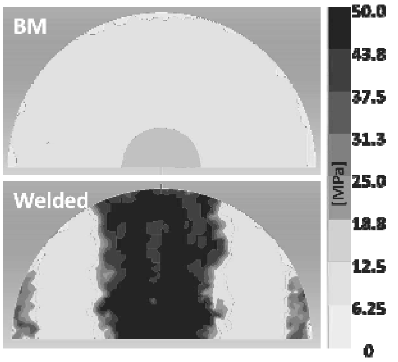

Figure 8. Von Mises stress distribution for the base material and FSWed sheet for a dome height corresponding to a safe condition.

The stress distribution found for the base material has a circular distribution with larger values around the punch, as expected for the tests characterized by length to width ratio equal to 1. On the contrary, a non symmetric distribution is found for the welded sheet, and a significant amount of stress is observed all along the welding line. Additionally, it should be observed that, although no necking is observed in the experiments for the shown dome height, the maximum stress value for the FSWed sheet is larger and distributed on a larger area than the one observed in the base material.

4. CONCLUSIONS

The formability of friction stir welded joints in AZ31 thin sheets, obtained using a "pinless" tool configuration, was evaluated both in terms of forming limit curves under warm forming condition. The results were compared with those obtained, under the same experimental conditions, on the base material. The experimental work was supported by a numerical investigation based on finite element method in order to highlight the material flow occurring during the welding process.

In particular, the formability exhibited by the FSWed joint is much lower than that of BM, both in terms of major strain values and the minor strain interval.

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