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In-process control of rotational speed in friction stir welding of sheet blanks with variable mechanical properties

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Abstract

In the present work, an adaptive control constraint system was applied in the friction stir welding of AA6082 aluminum alloy with the aim of tailoring the mechanical properties of the sheet blank to the subsequent forming processes. To this purpose, blanks in the solution heat-treated and artificially aged (T6), and in the annealed (O) conditions were welded according to a well defined layout. Such in-process control strategy was based on the variation of the controlled variable (rotational speed of the pin tool) in order to keep the measured one (vertical force) constant during the welding stage of the process. To this end, a preliminary investigation on the effect of the rotational speed, varying from 1000 to 2500 rpm, on the vertical force during FSW was performed. The capability of the proposed approach in friction stir welding sheet blanks with variable mechanical properties along the welding line was proven.

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Keywords: Friction stir welding; Aluminum alloy; Temper state; Adaptive control

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1. Introduction

Friction Stir Welding (FSW) is considered as one of the most promising technologies to obtain Tailored Welded Blanks (TWBs), that are semi-finished components consisting of at least two single sheets welded together prior to the forming process [1, 2]. The attitude of FSW in the obtaining of TWBs is related to the solid-state nature of the process that allows the avoidance or the severe reduction of the typical defects taking place during fusion welding techniques [3, 4]. In friction stir welding process, a rotating pin tool is inserted into the edges of the sheets to be joined, producing a stirring action, until the tool shoulder contacts the top surface of the sheets with a given plunge depth, thus generating a large amount of heat by friction. Then, the translation of the tool along the welding line allows the obtaining of the weld seam. Such features make FSW suitable to join alloys, considered un-weldable or difficult to be welded, with high levels of joint efficiency [5, 6].

TWBs are mainly developed in order to improve the properties of parts for their applications and to contribute to the weight reduction, that is particularly marked as they are made in low density and high strength alloys [7]. In spite of these advantages, problems can arise as the tailored welded blanks are subjected to sheet forming processes due to their nonuniform thickness and/or strength. In such applications, the TWBs can be replaced by the Tailored Heat Treat Blanks (THTBs) developed to allow an enhancement in formability [8, 9]. A THTB is obtained by subjecting the sheet blank to a local heat treatment in order to tailor the mechanical properties to the subsequent forming processes instead of the final application. The most used materials are precipitation hardening aluminum alloys and high strength steels. The critical aspect in the production of the THTBs is the heat treatment in terms of stability, robustness, layout, occurrence of heat affected zones, and heating technology.

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An alternative process to improving formability in localized zones of sheet blanks could consist in friction stir welding blanks subjected to different heat treatments and positioned according to a suitable layout, defined taking into account the subsequent forming processes. Since FSW is performed by joining dissimilar materials or materials with mechanical properties variable along the welding line, the choice of the process parameters is the most critical aspect in order to obtain desired results [5]. The utilization of an in-process control strategy, able to adjust the process parameters on the basis of mechanical properties of the materials being welded, can strongly increase the success of the FSW of blanks subjected to different treatments. Recently, a method was developed in FSW of AZ31 magnesium alloy sheets with variable thickness along the welding line; it consists in adjusting the rotational speed of the pin tool in order to keep constant the vertical force (F) during the welding stage of the process [10]. If the F value corresponds to the condition that provides the best mechanical properties of the joint, the FSW process of blanks subjected to different temper states is optimized.

In this framework, the present work deals with the application of an in-process control strategy in the friction stir welding of AA6082 aluminium alloy in two different states, namely in the solution heat-treated and artificially aged (T6), and annealed (O) states. Such approach is based on the variation of the rotational speed of the pin tool in order to keep the vertical force constant during the welding stage of the process. The experimental tests have proven the capability of the proposed approach to join at high efficiency sheet blanks with variable mechanical properties along the welding line.

2. Material and experimental procedures

Friction stir welding experiments were performed on a CNC machining center. The 2 mm thick sheets in AA6082 aluminium alloy, supplied in the solution heat-treated and artificially aged (T6), were cut into blanks, 60 mm in length, and 80 mm in width; then, part of them were subjected to the annealing heat treatment (O).

The FSWed blanks were obtained by means of a two-step process. In the first step, dissimilar joints were obtained by welding two blanks in T6 and O states; the blank in the T6 state was positioned in the advancing side (Fig. 1a). In the second step, the dissimilar joints were assembled according to the layout shown in Fig. 1b in order to weld blanks with variable mechanical properties along the welding line.

Experiments were carried out by equipping the machining center with an adaptive control constraint (ACC) system that allows to adjust the rotational speed (ω) of the pin tool with the aim to keep the vertical force (F) arising during the welding stage of the process at a value depending on the mechanical properties of the material being welded. The F value was measured by means of a sandwich dynamometer, developed by Forcellese et al. in [11], consisting in three piezoelectric one-component force sensors fitted between two rigid plates with a high preload (Fig. 2).

A preliminary investigation on the effect of the rotational speed on the vertical force during FSW was also performed. To this purpose, FSW experiments were carried out for the obtaining of similar joints both in the O and T6 states (Fig. 1c); different rotational speeds, varying from 1000 to 2500 rpm, were investigated with a constant welding speed equal to 60 mm/min.

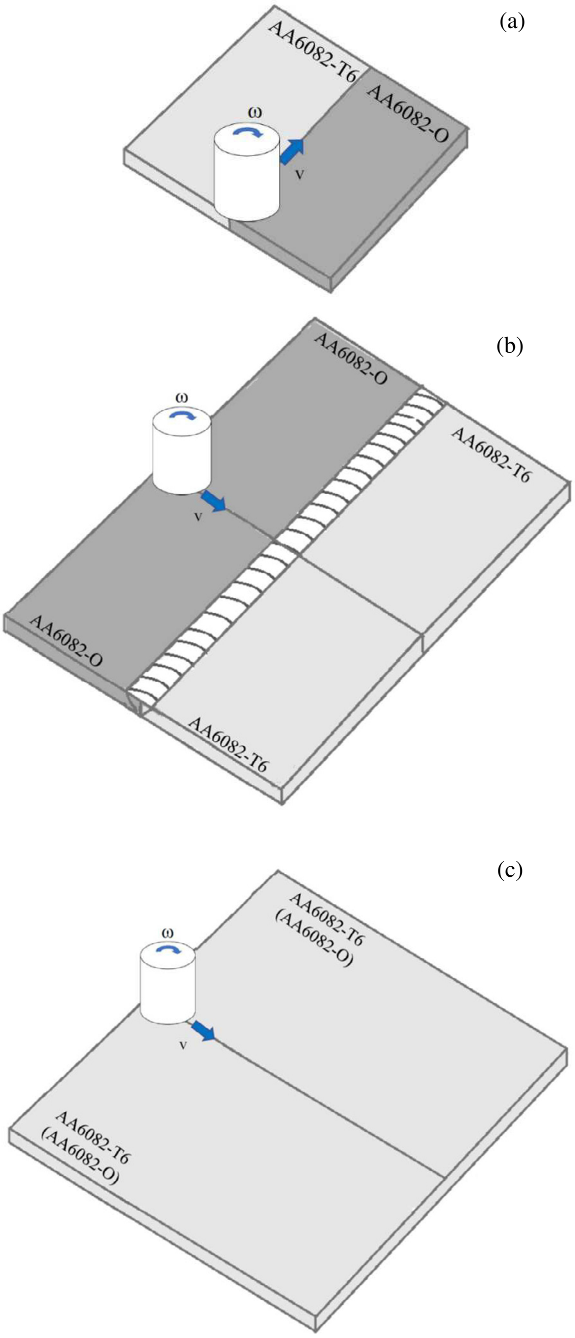

Fig. 1. (a) Positioning of the sheet blanks in FSW of dissimilar joints; (b) positioning of dissimilar joints in FSW of blanks with variable mechanical properties along the welding line; (c) positioning of blanks in FSW of similar joints.

Fig. 2. Sandwich dynamometer used to measure the vertical force developed during FSW.

All the friction stir welding trials were carried out with a plunging speed equal to 1.5 mm/min, and plunging depth of 0.1 mm. The rotating pin tool was in H13 tool steel, with the shoulder diameter of 12 mm, cone base diameter of 3.5 mm, cone height of 1.7 mm, pin angle equal to 30°, and tilt angle of 2°. At least three FSW repetitions were performed for each testing condition.

The mechanical properties of the FSWed joints were evaluated by room temperature uniaxial tensile tests carried out on the servo-hydraulic testing machine MTS 810 according to the ASTM E8/E8M [12] and BS EN 895 [13] standards. Samples with gauge length equal to the shoulder mark were machined from the welded blanks with the loading direction perpendicular to the welding line. During testing, the nominal stress (s) and nominal strain (e) data were recorded; by analyzing the s-e curves, the Ultimate Tensile Strength (UTS) and Ultimate Elongation (UE) were calculated. For each testing condition, at least three tensile tests were performed.

3. Results and discussion

Fig. 3 shows typical vertical force vs. time curves measured during friction stir welding of similar sheet blanks in AA6082 alloy according to the layout reported in Fig. 1c. Irrespective of the temper state and process condition, the F-t curve is characterized three stages. In the first one, the primary plunging, during which the pin penetrates into the sheets, is followed by the secondary one, during which the shoulder contacts the top surface of the sheets. The F value increases at the beginning of the pin sinking due to the strengthening of the workpiece material. Then, the softening caused by the heat generated by the stirring action of the pin prevails on the strengthening and the vertical force decreases with increasing time. In the final part of the pin plunging, the F value gets back to grow owing to the cooling caused by the heat exchange at the sheet-backing plate interface; at the contact tool shoulder - sheet surface, the F value further increases owing to the growth in the frictional work and amount of the stirred material. In the second stage of the F-t curve, the combined effect of the tool rotation and translation along the welding line produces a steady state regime with constant value of the vertical force as a function of time. In the last stage of the process, the pulling out of the pin from the blanks causes a sharp decrease to zero in the F value. The behavior exhibited by the F-t curve of AA6082 alloy is very close to the one shown by the AZ31 magnesium alloy under similar process conditions [11].

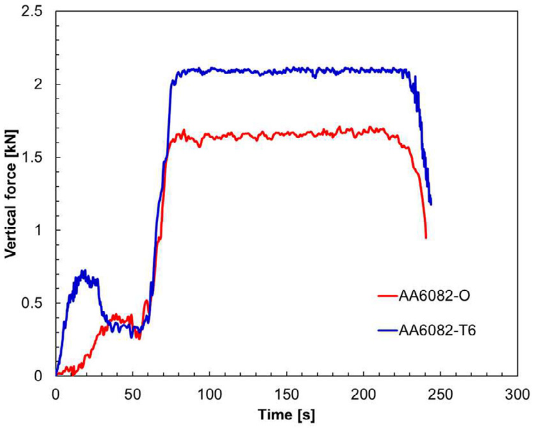

Fig. 3. Effect of the temper state on typical vertical force vs. time curves measured during friction stir welding of similar joints (ω=2500 rpm; v=60 mm/min).

Fig. 3 also shows that, irrespective of the stage of the F-t curve considered, for a giver rotational speed, the vertical force obtained during FSW of AA6082 in the annealed state is always lower than that of the alloy in the solution heat-treated and artificially aged state. Such discrepancy has to be attributed to the lower strength of the alloy in the O state as compared to the one in the T6 condition.

The steady state value of the vertical force taking place in the welding stage as a function of the rotational speed in shown in Fig. 4. It appears that, irrespective of the temper state, the F value monotonically decreases with rising the rotational speed due to the increase in the heat input into the joint with ω [3, 11].

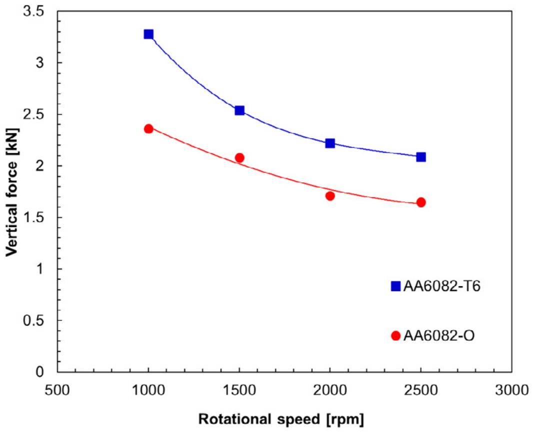

Fig. 4. Influence of the temper state on the steady state values of the vertical force taking place during the welding stage of similar joints as a function of the rotational speed.

Fig. 5 shows typical nominal stress – nominal strain curves obtained by tensile tests carried out on AA6082 joints. Irrespective of the rotational speed, it can be seen that the O condition leads to lower strength and higher ductility levels than those of the T6 one. Finally, the UTS vs. ω data, in both the temper states, are shown in Fig.6. The rotational speed that allows the obtaining of the highest tensile strength is equal to 2000 rpm in the O state and 1500 rpm in the T6 one.

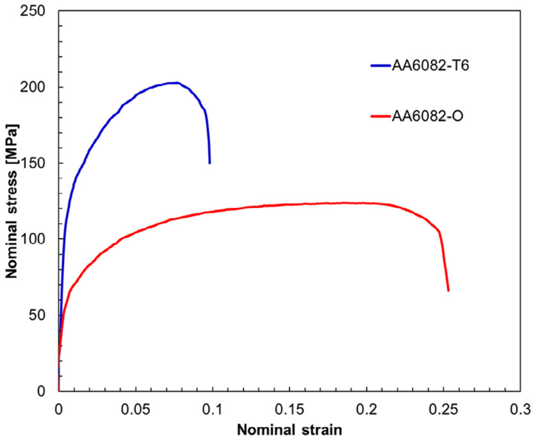

Fig. 5. Effect of the temper state on typical nominal stress – nominal strain curves provided by tensile tests carried out on samples obtained by similar joints (ω=2500 rpm; v=60 mm/min).

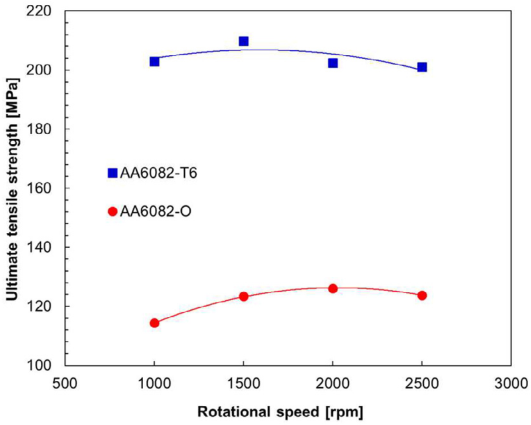

Fig. 6. Influence of the temper state on the ultimate tensile strength of similar joints vs. rotational speed plots.

On the basis of the analysis of the results obtained on the similar joints, FSW tests were carried out on AA6082 sheets with variable mechanical properties along the welding line, according to the layout shown in Fig. 1a. In previous papers [5, 6], it was shown that the mechanical properties and microstructure of dissimilar joints are strongly affected by the position of the blanks in different materials/treatments with respect of the welding line. As a matter of fact, the mechanical properties exhibited by the joints are related, besides of the mechanical properties of the base alloys, to the heat distribution into the workpieces during FSW; since the advancing side is characterized by a resultant velocity vector higher than that in the retreading one, the maximum temperature profile in the advancing side is higher than that in the retreating one. The discrepancy between temperatures of the two sheet blanks joined becomes more marked as dissimilar materials are welded due to the different strength levels exhibited by AA6082 alloy in the T6 and O temper states. In order to take advantages from the temperature distribution inside the weld during FSW and to facilitate the mixing across the joint, the blank in the T6 state was positioned in the advancing side, whilst that in the O condition in the retreating one (Fig. 1a).

The approach followed in the present work was based on the maintaining the vertical force constant during the welding stage by adjusting the ω value. In particular, the F value was kept equal to 1.7 kN and 2.5 kN, during welding of the alloy in the O and T6 states, respectively. These conditions were chosen in such a way that, for each temper state investigated, the FSW process would provide the highest value of mechanical strength. Fig. 7 shows the F-t behavior recorded during FSW using the proposed approach. It can be seen that, after plunging, the vertical force during the welding stage of the sheets in the O-annealed state keeps almost constant at the value of 1.7 kN. As the tool contacts the material in the T6 condition, the pin tool action occurs by simultaneously stirring the AA6082 in both temper states. In mixed zone, the vertical force grows due to the higher strength of the T6 material with respect to the annealed one. The response of the ACC system produces a decrease in the rotational speed until the vertical force reaches the value of 2.5 kN. Once the stirring action occurs in the material at the T6 state alone, the F value stabilizes until the pulling out stage occurs.

Finally, Fig. 8 shows the nominal stress – nominal strain curves of the joints obtained with the proposed approach. The results obtained are consistent with those given by similar joints welded according to the layout shown in Fig. 1c, confirming the validity of the proposed approach.

However, further studies on the microstructural development in the FSWed zones are in progress.

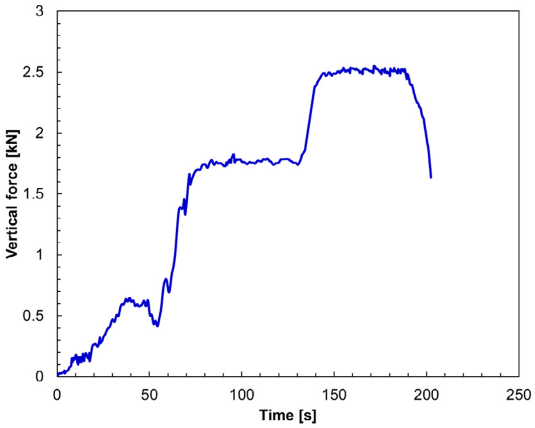

Fig. 7. Vertical force vs. time curve measured during friction stir welding of sheet blanks with variable mechanical properties along the welding line.

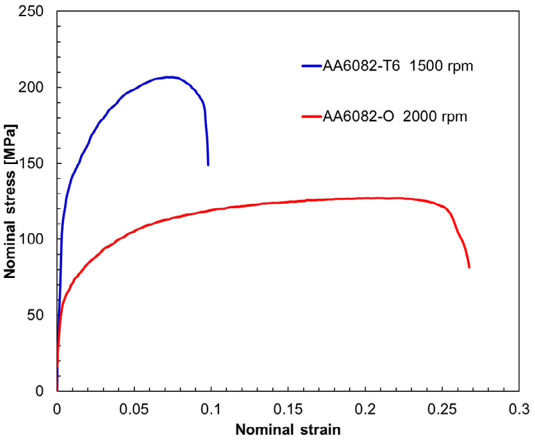

Fig. 8. Tensile curves obtained on samples taken in the different zones of the blank welded according to the layout of Fig. 1b.

4. Conclusions

In the present work, the application of an in-process control strategy in the friction stir welding of AA6082 aluminum alloy in the solution heat-treated and artificially aged, and annealed states, was investigated. Such approach is based on the variation of the rotational speed of the pin tool to keep the vertical force constant during the welding stage of the process. The main results provided by the preliminary FSW experiments for the obtaining of similar joints can be summarized as follows:

- the vertical force vs. time curve is characterized three stages, namely plunging, welding, and pulling out;
- for a giver rotational speed, the vertical force obtained during FSW of AA6082-T6 is always higher than that of AA6082-O;
- the steady state value of the vertical force taking place in the welding stage monotonically decreases with rising the rotational speed;
- the rotational speed that allows the obtaining of the highest tensile strength is equal to 2000 rpm in the annealed state and 1500 rpm in the solution heat-treated and artificially aged one.

On the basis of the analysis of the results obtained on the similar joints, FSW tests were carried out on sheets with variable mechanical properties along the welding line, using the in-process control strategy. The adaptive control system has proven the capability to weld the alloy in the optimal condition of the rotational speed.

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