Influence of welding parameters on the microstructure, thermal fields and defect formation in AA7075-T6 friction stir welds

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Abstract
This study focuses on the influence of the welding parameters on defectiveness, thermal field and grain size in friction stir welding of aluminium alloy 7075-T6. Different welded specimens were produced employing various rotational speeds and welding speeds. In the first part of the analysis, the quality of the joints was evaluated by microscopic observation of the jointed cross-sections to investigate the modification of the shape of the stirred zones and the occurrence of internal voids. Afterwards, temperature and grain size of welds obtained at welding speed of 60 mm/min have been measured to study the influence of the rotational speed on the heat input. Temperature measurements have been carried out with thermocouples and infrared camera. Grain size evolution of the material was analysed by optical observations of the jointed cross-sections and the average grain size in the nugget zone (NZ) has been estimated through electron backscatter diffraction. The results globally show that the first internal defects arose at the same time as an unexpected zone on the advancing side between the shoulder affected zone (SAZ) and NZ. In sound welds, from 800 to 1400 rpm, the peak temperature showed an increase between 5 and 15%, depending on the considered zone, while the grain size in the stirred zone increased from 2 to 3.6 μm. Overall, it has been shown that the approach to the defective condition is due to the low heat input which is responsible for improper material flow during the process.

Keywords Friction stir welding · Nugget zone · Temperature measurement · Grain size · Process parameters · AA7075-T6

1 Introduction
Friction stir welding (FSW) is a solid-state joining technology patented in 1991 by The Welding Institute [1]. This process has allowed the overcoming of the typical melting-related defects [2] as well as the production of high mechanical efficiency joints [3, 4] due to less severe thermal cycles. In the last 30 years, the process has been widely applied to aluminium alloy 7075 (Al-Zn-Mg-Cu) because of its high strength-to-weight ratio together with its natural ageing characteristics [2].

Over the years, the effect of manufacturing parameters on the FSW process has been extensively studied. Studies on the influence of process parameters on the mechanical properties of FSW joints have been proposed [5–8]. The evolution during the process of physical quantities such as forces and torque, depending on the welding parameters, has been analysed in order to further investigate the phenomenology within the stirred zone [9–12]. The effect of manufacturing parameters on the occurrence of internal and external defects has been shown during the years [13–20]. Some studies reported on microstructural modification during FSW due to different combinations of process parameters [5, 21, 22]. Also, several researchers focused on the influence of friction stir welding parameters on thermo-mechanical phenomena by analysing temperature, strain and strain rate during the process, both experimentally and numerically simulated [23–38].

The defectiveness of FSW joints has been showed to be strongly dependent on the employed welding parameters. Kim et al. [13] clarified the important role of axial force in FSW. The authors showed that higher values of axial force ensure a wider range of optimum FSW conditions. Chen
et al. [14] demonstrated how low values of the tilt angle can negatively affect the material flow causing voids formation in the nugget zone. An exhaustive analysis on the influence of the welding parameters on the defectiveness of AA7075-T6 FSW joint has been proposed by Rajakumar et al. [16]. The occurrence of flow defects by increasing the welding speed has been demonstrated by Zhang et al. [17]. Also, Ramulu et al. [18] showed that once non-defective welding configurations are reached, the response variables, such as forces and torque measured during the process, are almost constant. The authors pointed out that in the optimum range of welding parameters those quantities are insensitive to modification of the parameters. Rasti [19] showed the role of poor flow induced by low heat generation during the process for the occurrence of internal defects. The author proposed a model to calculate heat input during the process and identified the required minimum heat input to avoid the tunnel defect in FSW of AA1060.

The influence of process parameters on the grain size in friction stir welds has been widely studied over the years. In early works on FSW, Sato et al. [5] claimed that it is possible to identify three different regions depending on the microstructure in friction stir welds, namely heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ) and nugget zone (NZ). Cavaliere et al. [6] reported a decrease of the grain size in the nugget zone of AA6082-T6 joint from 2.8 to 2 μm employing a rotational speed of 1600 rpm and going from 40 to 460 mm/min. The influence of both rotational speed and feed rate on the grain size was studied by Long et al. [9]. The authors revealed the strong influence of the rotational speed on the grain size with an increase from 2 to 11 μm going from 100 to 600 rpm at constant feed rate during friction stir welding of AA7050. Imam et al. [22] showed the influence of the feed rate on the grain size. The authors found smaller grain size in the nugget zone for the welds performed at 48 mm/min compared to the one manufactured at 18 mm/min, employing the same rotational speed. Overall, the influence of the most influential weld parameters, namely feed rate and rotational speed, on the microstructural refinement during FSW has been properly summarised by Yi et al. [28]. The authors claimed that the grain size in the nugget zone during FSW is firstly influenced by the rotational speed that affects the peak temperature and then by the feed rate that affects the rate of the cooling cycle.

Temperature measurements during FSW have been widely performed and useful information has been gathered. First measurements performed embedding thermocouples both in workpieces or tools provided an estimation of the temperatures reached during the process. Mahoney et al. [33] measured the temperature during the FSW of AA7075 alloy estimating it below 400 °C in the HAZ, below 475 °C in the TMAZ and above 475 °C in the NZ. The asymmetry of the temperature distribution during FSW has been showed by Hwang et al. [34]. The authors measured the temperatures on the advancing side (AS) and retreating side (RS) measuring slightly higher values of temperature on the AS than RS. Several authors showed the influence of the welding parameters on the thermal field during FSW. Globally, it has been showed that the rotational speed strongly affects the reached peak temperature while the feed rate mostly influences the rate of the heating and cooling cycles [29, 35]. However, the influence of the rotational speed on the peak temperature, and as consequence on the heat input, has been demonstrated to be limited by the physics of the process. Once the sticking condition occurs and the friction coefficient drops, the heat is generated mainly through plastic deformation of the material. In these circumstances, heat generation is governed by flow stress, which continues to decrease as the temperature increases and the alloy softens. For this reason, the rate of temperature increase first slows down and then stops when the steady state is reached [29, 35–37]. Unlike thermocouples, infrared (IR) cameras have not been often used to measure temperatures during the FSW process. However, the same temperature trends were found when measuring with IR cameras [38].

Although many researchers have studied the influence of manufacturing parameters on friction stir welding joints, an investigation concerning the occurrence of internal defects completed by data on heat input during the process (temperature and grain size) is still lacking. The objective of this study is therefore the understanding of the influence of process parameters on defectiveness, thermal field and grain size during FSW of AA7075-T6 alloy. In the first part, cross-section of manufactured welds are analysed to investigate the changes in the shape of the stirred zones and the occurrence of internal voids. Secondly, because of differences found in the shape of the stirred zones in non-defective joints, further investigations are carried out to quantify the qualitative observations made during the first analysis. Temperature and grain size measurements are conducted to study their evolution with the rotational speed. The final results showed that the approach of the defective condition is due to the low heat input that is responsible for poor flow during the process. The heat input in the different configurations has been studied through the experimental evaluation of the temperature in various zones during the process and with postmortem measurement of the grain size in the nugget zone. As a guideline, the minimum required temperatures to be guaranteed in TMAZ and HAZ to achieve a sound weld in friction stir welding of AA7075-T6 are proposed.
2 Experimental procedures

2.1 FSW procedure specification

The materials used were 3-mm thick-rolled sheets of AA7075-T6. Bead-on-plate welds 80 mm long were performed along the rolling direction with various welding parameters. All the welds have been performed in force control, and the different chosen process parameters are listed in Table 1. The applied axial force has been fixed at 5.5 kN for all the welds. This value was found experimentally after several attempts to obtain a sound weld at 800 rpm and 60 mm/min with the lowest axial force possible. The choice of this minimum axial force was made in order to likely obtain defective joints by increasing the feed rate during the experimental campaign and then analyse the internal defects. The possible achievement of defective joints by increasing the feed rate is due to the low axial force value chosen and kept constant for all joints. The robot used for the production of the joints was a KUKA KR500-3MT equipped with an ACTEMIUM BPA-6700 spindle. The tool employed was characterised by a grooved shoulder and a slightly tapered threaded M4 pin (Fig. 1). The diameter of the shoulder was 12 mm and the pin was 2.8 mm in height. A mild steel anvil was used as backing plate. All the welds have been performed with a tilt angle of 1.8°.

2.2 Joints inspection

The cross-section of the joints were inspected firstly to evaluate modification in the shape of the stirred zone and the occurrence of internal voids and secondly to measure the grain size in the NZ. The welds were analysed by making optical microscope observations (Olympus PMG3). Samples were taken at the second half of the joint to ensure the steady state of the process. Subsequently, the samples were prepared by standard metallographic techniques. Keller’s reagent was used to etch the surfaces in order to reveal the grain structure within the section. The information regarding the grain size was obtained from the EBSD analysis. The analysed specimens underwent electrolytic polishing using a reagent consisting of 720 mL ethanol (C₂H₅OH), 120 mL ethylen-glycolmonobutylether (C₆H₁₄O₂), 90 mL H₂O and 75 mL perchloric acid (HClO₄).

Table 1 Employed process parameters

| Welding speed (mm/min) | Rotational speed (rpm) |
|------------------------|------------------------|
| 60                     | 800–1000–1200–1400     |
| 180                    | 1000–1200–1400–1600    |
| 300                    | 1000–1200–1600–1800    |

2.3 Temperature measurements

The measurements with thermocouples and IR cameras have been carried out repeating some experiments. Bead-on-plates 140 mm long were performed. The plates were black-painted to control the emissivity and calibrate the measurement with the IR camera. The values of axial force and torque measured by the robot during tests performed on painted and normal plates, using the same welding parameters, have been compared. Differences of trends and average values between those quantities in the two configurations were neglectable. Therefore, it was considered that the presence of the painting did not affect the process.

Transient temperatures were recorded during the FSW process using three K-type thermocouples (accuracy 2 °C). The temperature measurements were acquired by a National Instruments DAQ system at 15 Hz. Three holes with a diameter of 3 mm and some slots on the bottom surface of the anvil were made to accommodate the thermocouples. The distance between the centre of the holes and the joint line were 3 and 6 mm on the RS and 6 mm on the AS. The sensors were positioned vertically with respect to the plates to be welded so that only the tip of the thermocouples was out of the hole and placed between the welding plates and the backing plate. The thermocouples were fixed in the holes with high thermal conductivity OMEGA® CC High Temperature Cement to ensure the seal during the process. The effective position of the tips of the thermocouples after welding with respect to the joint line were verified by checking the mark of the thermocouples on the welded plate and were 3 mm (TC₁) and 7 mm (TC₃) on the RS and 6 mm (TC₂) on the AS. The first sensors were placed 60 mm away from the plunging point to ensure that the measurements were carried out in the steady state of the process. In Fig. 2, a scheme on the positioning of thermocouples is presented. IR temperature fields measurements were performed with an IR camera CEDIP® Jade III MWIR retrofitted FLIR® titanium SC 7200 with a thermal resolution of 20 mK at 30 °C (further information on the IR camera and on the
Fig. 2 Experimental setup for thermocouples. a Holes and slots on the anvil for the thermocouples placement. b Thermocouples placement in a traverse section view by imagining the thermocouples in the same plane.

(a) Holes and slots on the anvil for the thermocouples placement

(b) Thermocouples placement in a traverse section view by imagining the thermocouples in the same plane.

Experimental setup in Fig. 3. Calibration and data recording were managed by the Altair software. The IR camera was fixed and placed behind the welding starting point, as showed in Fig. 3. Considering the configuration and the stationary IR camera, the acquisition was possible only in the first 60 mm of the weld.

3 Results

3.1 Cross-sections inspection

The cross-sections of welds performed at 60 mm/min are displayed in Fig. 4. Firstly, comparing the four cross-sections, a clear separation between the shoulder affected zone (SAZ) and the NZ can be observed, as highlighted in Fig. 4d. All the nugget zones presented the typical banded structures known as onion rings. Despite the similar aspects of the four sections, comparing Fig. 4a with the others, it is possible to notice a slight difference in the shape of the nugget zones. While NZ in Fig. 4b, c, d presented the typical elliptical shape, in the joint performed at 800 rpm, the shape of the nugget zone is more bell-shaped than elliptical.
Fig. 5 Magnification of the transition zone at 60 mm/min and 800 rpm

as showed in the dotted lines around the NZ in Fig. 4a. Also, looking further into the detail Fig. 4a, the transition between SAZ and NZ is more noticeable especially in the zone of the AS. A magnification of this transition zone is displayed in Fig. 5. Two particular features stand out from this image. The first is the appearance of a small triangular area, highlighted in Fig. 5, between the SAZ and the NZ on the AS. The second is the occurrence of micro-voids (approximately 15 μm wide) exactly along the chaotic transition zone between SAZ and NZ.

In Fig. 6, the transverse section of welds made at 180 mm/min are shown. Looking at the four cross-sections, it is possible to divide them into two sub-groups. The first one, 1000 and 1200 rpm, where the inner defects extend until the external surfaces, while in the second group, 1400 and 1600 rpm, the lack of material is kept within the NZ.

Fig. 6 Weld cross-section macrographs at 180 mm/min. a 1000 rpm. b 1200 rpm. c 1400 rpm. d 1600 rpm

Fig. 7 Weld cross-section macrographs at 300 mm/min. a 1200 rpm. b 1600 rpm. c 1800 rpm
In Fig. 6a, b, it is notable that the extension of the width of the nugget zone is significantly reduced compared to welds obtained at 60 mm/min. In both cross-sections, the absence of material starts within the NZ and then it develops along the SAZ reaching the external surface. For the joints characterised by higher rotational speed, only internal defects can be observed. The first feature to highlight is the even more remarkable distinction between NZ and SAZ compared to welds made at 60 mm/min. Also, the vertical extension of the SAZ in Fig. 6c, d seemed to be significantly increased occupying more than half of the thickness of the cross-section. In both cross-sections, it is interesting to observe the occurrence of small internal defects on the AS exactly along the transition zone between SAZ and NZ, as showed in Fig. 6c, d by the white-dotted lines. Furthermore, the previously introduced triangular zone between SAZ and NZ on the AS can be observed again. Lastly, the shape of the banded structures in the NZ presented a more chaotic shape with a sudden deviation between the NZ and the triangular zone on the AS.

Welds performed at 300 mm/min are shown in Fig. 7. The cross-section of the weld obtained at 1000 rpm has not been analysed because it presented already huge external defects. In the joint showed in Fig. 7a, a considerable void in the inner part of the NZ that extends until the weld crown can be observed. As for the welds obtained at 180 mm/min employing the lower rotational speeds, the width of the NZ is significantly reduced if compared with welds obtained at 60 mm/min. Analysing the cross-sections in Fig. 7b, c, it is worthy noting the presence of several small voids randomly placed in the SAZ on the AS, as evidenced by the dotted circles in the figures. Some of these small voids extend until the external surface of the joints. It is interesting to report, as already observed previously for some of the welds obtained at 180 mm/min, the deformation of the banded structures for cross-sections displayed in Fig. 7b, c. Lastly, another interesting feature can be recognised looking at the magnification of the cross-section in Fig. 7b showed in Fig. 8. Some of the grains in the transition zone between NZ and SAZ are more similar to the ones in the TMAZ than to the typical equiaxed refined microstructure of the NZ encountered in all the analysed cross-sections.

### 3.2 Temperature measurements

The temperature versus time curves obtained with thermocouples are displayed in Figs. 9, 10 and 11. The curves have
been shifted along the x-axis in order to ease their reading and avoid the overlapping. Table 2 summarises all the peak temperatures obtained during the various weldings.

In Fig. 9, it is possible to observe the influence of the rotational speed on the peak temperature at a 3-mm distance from the welding line on the RS. It is relevant that all the measured maximum temperatures were above 400 °C. From 800 to 1000 rpm, a 3% increase can be observed. Then, after the stabilisation between 1000 and 1200 rpm, another slight increase is registered between 1200 and 1400 rpm. By comparing the welds obtained at 800 and 1400 rpm, the peak temperature is increased by 5%. Temperature measurements made with TC2 are shown in Fig. 10. In this case, all the measured temperatures were always below 400 °C. After an increase by 6% from 800 to 1000 rpm, the value of the peak temperature stabilised around 370 °C in all the other configurations. The trend of the temperatures measured by TC3 is shown in Fig. 11. It is possible to observe an increase in the peak temperature by 8% between 800 and 1000 rpm, a further increase by 4% between 1000 and 1200 rpm and then a stabilisation around 350 °C between 1200 and 1400 rpm. Overall, the peak temperature is increased by 12% from 800 and 1400 rpm.

Table 2 Peak temperature measured with thermocouples at 60 mm/min

| Thermocouple | 800 rpm (°C) | 1000 rpm (°C) | 1200 rpm (°C) | 1400 rpm (°C) |
|--------------|--------------|---------------|---------------|---------------|
| TC1          | 405          | 415           | 415           | 424           |
| TC2          | 347          | 369           | 372           | 372           |
| TC3          | 312          | 338           | 350           | 350           |

From the temperature fields measurements performed with the IR camera, data on the temperatures on the top surface of the welded plates have been obtained. The temperatures at a 6-mm distance from the welding line, right after the edges of the shoulder on both sides, have been calculated. On both sides, these values have been estimated by averaging the temperature of 4 points taken in the second part of the 60 mm of welding during which the acquisition took place, in order to be in the steady state of the process. The choice was made to measure the temperature at the closest location to the welding line and accessible by
Table 3 Average values and standard deviation of temperature measurements with IR camera

| Welding line distance (mm) | 800 rpm (°C) | 1000 rpm (°C) | 1200 rpm (°C) | 1400 rpm (°C) |
|---------------------------|--------------|--------------|--------------|--------------|
| 6 (RS)                    | 372 ± 10     | 400 ± 7      | 416 ± 6      | 423 ± 10     |
| 6 (AS)                    | 376 ± 11     | 413 ± 5      | 419 ± 2      | 433 ± 4      |

the IR camera. A sketch of the IR camera view where the points used for calculating the temperatures are reported is shown in Fig. 12. The trends of the temperature measured on the AS and RS are shown in Fig. 13. The average values and standard deviation of the temperature are summarised in Table 3. It is noteworthy that the values on the AS are slightly higher than those on the RS. The highest temperature increase is found between 800 and 1000. The temperature increased by 10% and 8% on the AS and RS, respectively. Globally, between 800 and 1400 rpm, the temperature increased approximately by 15%.

3.3 Grain size

The microscopic observations of the microstructure in the NZ of the welds made at 60 mm/min employing various rotational speeds are displayed in Fig. 14.

Fig. 14 Microscopic observation in the nugget zone of welds made at 60 mm/min. a 800 rpm. b 1000 rpm. c 1200 rpm. d 1400 rpm

Qualitatively, it is possible to notice the continuous increase in the grain size from 800 to 1400 rpm. The grains become progressively wider for higher rotational speed. To accurately calculate the fine grain size in the NZ, the EBSD technique was used to analyse samples at 800 and 1400 rpm. The results confirmed what had been predicted by optical microscopic observations with an increase from 2 to 3.6 μm in the average grain size.

4 Discussion

The results show the influence of the welding parameters on the weld quality in FSW. Three different types of joints have been identified and classified into sound welds, welds characterised by internal defects and those with both internal and external defects. Figure 15a displays the outcomes of all the combinations of process parameters tested. For each configuration, the heat input during the process was estimated through the empirical model proposed by Pew et al. [39], which determines the heat input from the spindle torque measured during the welding. Although this model does not consider the heat loss that it is known to be affected by the process parameters [28], it provides an idea of the amount of heat generated during the process varying the welding conditions. The heat input for all the welding is displayed in Fig. 15b.
Fig. 15  Welding configurations. a Weldability window. b Heat input as function of the rotational speed

Sound welds have been obtained only employing a feed rate of 60 mm/min. The result is not unexpected because the fixed axial force (5.5 kN) was calibrated to obtain proper welds with this feed rate. This combination of axial force and feed rate seems to guarantee the success of the process for a wide window of rotational speed (from 800 to 1400 rpm). In those conditions, the process is stable, the temperatures allow the suitable material flow in the stirred zone with the consequent proper filling of the cavity left by the tool during its simultaneous advancing and rotation. Welds characterised by internal defects have been produced at 180 mm/min employing the higher rotational speeds (1400 and 1600 rpm). In those configurations, the shoulder seems to be capable of dragging the material during its rotation avoiding the lack of material in the weld crown. However, internal defects located mainly along the transition zone between NZ and SAZ occurred. Through the analysis of the macrographs displayed in Fig. 6c, d, the chaotic nature of the process is noticeable. The SAZ extend for more than half the plate thickness appearing to squeeze the NZ (Fig. 6c). The consequence of this compression of the NZ is the formation of the third zone on the AS between SAZ and NZ where the majority of the internal defects appear. Under non-optimal welding conditions, the onion rings structure does not fully occur with the generation of a hybrid configuration characterised by the unexpected zone, as shown in Fig. 16.

It seems clear, therefore, that for these values of welding speed and axial force, the complete filling of the cavity left by the tool is not possible even for the highest rotational speed. The cause has to be found in the low heat input in joints made at the highest welding speeds (180 mm/min and 300 mm/min), as displayed in Fig 15b. The inadequate welding condition prevents the achievement of the sticking condition and the consequent stability of the process [36, 37]. Failure to achieve the sticking condition is due to the low temperature reached that impedes the correct material flow. The final result is the generation of internal voids in the transition zone between SAZ and NZ on the AS. Confirmation of incorrect mixing is provided not only by the internal voids but also by the marked distinction between SAZ and NZ if compared with the macrographs of sound welds in Fig. 4. All the other welds present internal defects of different sizes that develop up to the
weld crown due to increasingly severe working conditions. In particular, the presence of deformed grains similar to the ones in the TMAZ, in the transition between NZ and SAZ, in the weld made at 300 mm/min and 1600 rpm is shown in Fig. 8. This finding suggests that the material has not been properly stirred during tool rotation and feed. Therefore, under unfavourable welding conditions characterised by high welding speeds, the material seemed to be discontinuously cut and released within the weld wake rather than being dragged by the tool in a continuous flow, remaining blocked in the form of severely deformed grains. This result confirms the existence of certain similarities between chip morphology in machining and the cyclic deposition of shear layers in FSW [40].

The condition of incorrect material mixing can be explained through the critical case found by analysing the macrographs of the joints obtained at 60 mm/min in Fig. 4. It is possible to clearly distinguish the joint obtained at 800 rpm from the other three. The slight change in the shape of the NZ, the appearance of the small third zone between NZ and SAZ on the AS and the occurrence of micro-voids in the same zone obtained employing the lower rotational speed indicate an initial approach to unsuitable welding condition. The plausible explanation is that the configuration at 800 rpm and 60 mm/min with an applied axial force of 5.5 kN represents a boundary manufacturing condition between a defective and non defective joint and does not fully ensure the attainment of the sticking condition to stabilise the process and allow a correct mixing of the material.

The measurements made with both thermocouples and IR camera have confirmed that the highest increase in temperature takes place between 800 and 1000 rpm. Afterwards, from 1000 to 1400 rpm, the temperatures seem to stabilise. Considering the areas of investigation, measurements made with the IR camera and TC1 are measurements in the TMAZ, while the others made with TC2 and TC3 are temperatures in the HAZ. The scheme that summarises the points where the temperatures have been measured is shown in Fig. 17.

In accordance with the measurements carried out, the optimal welding conditions are verified if minimum temperatures of around 400 °C and 350 °C in the TMAZ and HAZ, respectively, are reached. These guideline values are in good agreement with other temperature ranges given in early studies by Mahoney et al. [33] for the same alloy.

Lastly, the effective influence of the different rotational speeds on the heat input was confirmed by the measurements made on the grain size. The average grain size in the NZ almost doubled, from 2 to 3.6 μm, confirming the strong influence of the rotational speed. The distribution of grain diameters in the areas analysed with EBSD are shown in Fig. 18. The temperatures reached during the process at higher rotational speeds affect the energy available for grain growth, and thus the final microstructure. Obviously, the final grain size is influenced not only by the peak temperature but also by the strain rate, as expressed by the Zener–Hollomon parameter [22]. Unfortunately, the determination of the maximum temperature in the stirred zone and the estimation of the strain rate are outside the scope of this work.

5 Conclusions

In this study, the influence of the welding parameters on defectiveness, thermal field and grain size in friction stir welding of aluminium alloy 7075-T6 has been presented. Two different analyses were carried out, the first on the quality of all joints and the second on the differences in temperature and grain size between the joints obtained.
at 60 mm/min. From the global point of view, it has been demonstrated that the improper material flow is distinguishable from the marked separation between SAZ and NZ and the occurrence of internal voids in their transition on the AS. Improper flow conditions occur when the optimum temperature, and therefore the correct heat input during the process, is not reached. The consequence is the difficulty for the material to be dragged and correctly deposited by the tool during the process.

The detailed examination of joints obtained at 60 mm/min allowed an in-depth analysis of the transition from non-defective to defective joint. The three characteristics found in the macrograph of the joint obtained at 800 rpm, i.e., the modified shape of the nugget, the appearance of the small third zone between NZ and SAZ on the AS and the micro-void appeared in the same zone, confirm the improper material flow. These qualitative experimental findings were quantitatively confirmed by temperature and grain size measurements. Minimum temperature values to be achieved to obtain a non-defective joint were identified around 400 °C and 350 °C in TMAZ and HAZ, respectively.

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References

1. Thomas WM, Nicholas ED, Needham JC, Murch MG, Templesmith P, Dawes CJ (1995) U.S. Patent No. 5,460,317, October 24
2. Mishra R, Komarasamy M (2016) Friction stir welding of high strength 7XXX aluminum alloys. Butterworth-Heinemann, Denton
3. Ericsson M, Sandström R. (2003) Influence of welding speed on the fatigue of friction stir welds, and comparison with MIG and TIG. Int J Fatigue 25(12):1379–1387
4. Yan Z, Liu X, Fang H (2017) Mechanical properties of friction stir welding and metal inert gas welding of Al-Zn aluminum alloy joints. Int J Adv Manuf Technol 91(9-12):3025–3031
5. Sato YS, Kokawa H, Enomoto M, Jogan S (1999) Microstructural evolution of 6063 aluminum during friction-stir welding. Metall Mater Trans A Phys Metal Mater Sci 30(9):2429–2437
6. Cavaliere P, Squillace A, Panella F (2008) Effect of welding parameters on mechanical and microstructural properties of AA6082 joints produced by friction stir welding. J Mater Process Technol 200(1–3):364–372
7. Fuller CB, Mahoney M, Calabrese M, Micona L (2010) Evolution of microstructure and mechanical properties in naturally aged 7050 and 7075 Al friction stir welds. Mater Sci Eng A 527(9):2233–2240
8. Imam M, Biswas K, Racherla V (2013) On use of weld zone temperatures for online monitoring of weld quality in friction stir welding of naturally aged aluminium alloys. Mater Des 52:730–739
9. Long T, Tang W, Reynolds AP (2007) Process response parameter relationships in aluminum alloy friction stir welds, 12(4):311–317
10. Cui S, Chen ZW, Robson JD (2010) A model relating tool torque and its associated power and specific energy to rotation and forward speeds during friction stir welding/processing. Int J Mach Tools Manuf 50(12):1023–1030
11. Su H, Wu CS, Pittner A, Rethmeier M (2013) Simultaneous measurement of tool torque, traverse force and axial force in friction stir welding. J Manuf Process 15(4):495–500
12. Astarita A, Squillace A, Carrino L (2014) Experimental study of the forces acting on the tool in the friction-stir welding of AA 2024 T3 sheets. J Mater Eng Perform 23(10):3754–3761
13. Kim YG, Fuji H, Tsumura T, Komazaki T, Nakata K (2006) Three defect types in friction stir welding of aluminum die casting alloy. Mater Sci Eng A 415(1–2):250–254
14. Chen H, B. i. n., Yan K, Lin T, Chen S, B. e. n., Jiang CY, Zhao Y (2006) The investigation of typical welding defects for 5456 aluminum alloy friction stir welds. Mater Sci Eng A 433(1–2):64–69
15. Khan NZ, Siddiquee AN, Khan ZA, Shihab SK (2015) Investigations on tunneling and kissing bond defects in FSW joints for dissimilar aluminum alloys. J Alloys Compd 648:360–367
16. Rajakumar S, Muralidharan C, Balasubramanian V (2011) Influence of friction stir welding process and tool parameters on strength properties of AA7075-T6 aluminum alloy joints. Mater Des 32(2):535–549
17. Zhang H, Lin SB, Wu L, Feng JC, Ma SL (2006) Defects formation procedure and mathematical model for defect free friction stir welding of magnesium alloy. Mater Des 27(9):805–809
18. Ramulu PJ, Narayanan RG, Kailas SV, Reddy J (2013) Internal defect and process parameter analysis during friction stir welding of Al 6061 sheets. Int J Adv Manuf Technol 65(9–12):1515–1528
19. Rasti J (2018) Study of the welding parameters effect on the tunnel void area during friction stir welding of 1060 aluminium alloy. Int J Adv Manuf Technol 97(5–8):2221–2230
20. Zeng XH, Xue P, Wang D, Ni DR, Xiao BL, Wang KS, Ma ZY (2018) Material flow and void defect formation in friction stir welding of aluminium alloys. Sci Technol Weld Join 23(8):677–686
21. Su JQ, Nelson TW, Mishra R, Mahoney M (2003) Microstructural investigation of friction stir welding 7050-T651 aluminium. Acta Mater 51(3):713–729
22. Imam M, Racherla V, Biswas K, Fujii H, Chintapenta V, Sun Y, Morisada Y (2017) Microstructure-property relation and evolution in friction stir welding of naturally aged 6063 aluminium alloy. Int J Adv Manuf Technol 91(5–8):1753–1769
23. Chao YJ, Qi X, Tang W (2003) Heat transfer in friction stir welding - experimental and numerical studies. J Manuf Sci Eng Trans ASME 125(1):138–145
24. Song M, Kovacevic R (2003) Thermal modeling of friction stir welding in a moving coordinate system and its validation. Int J Mach Tools Manuf 43(6):605–615
25. Nandan R, Roy GG, Debroy T (2006) Numerical simulation of three dimensional heat transfer and plastic flow during friction stir welding. Metall Mater Trans A Phys Metall Mater Sci 37(4):1247–1259
26. Masaki K, Sato YS, Maeda M, Kokawa H (2008) Experimental simulation of recrystallized microstructure in friction stir welded Al alloy using a plane-strain compression test. Scr Mater 58(5):355–360
27. Morisada Y, Imaiuzumi T, Fujii H (2015) Clarification of material flow and defect formation during friction stir welding. Sci Technol Weld Join 20(2):130–137
28. Yi D, Onuma T, Mironov S, Sato YS, Kokawa H (2017) Evaluation of heat input during friction stir welding of aluminium alloys. Sci Technol Weld Join 22(1):41–46

29. Peel MJ, Steuwer A, Withers PJ, Dickerson T, Shi Q, Shercliff H (2006) Dissimilar friction stir welds in AA5083-AA6082. Part I: process parameter effects on thermal history and weld properties. Metall Mater Trans A Phys Metall Mater Sci 37(7):2183–2193

30. Fehrenbacher A, Duffie NA, Ferrier NJ, Pfefferkorn FE, Zinn MR (2014) Effects of tool-workpiece interface temperature on weld quality and quality improvements through temperature control in friction stir welding. Int J Adv Manuf Technol 71(1–4):165–179

31. Silva ACF, De Backer J, Bolmsjö G (2017) Temperature measurements during friction stir welding. Int J Adv Manuf Technol 88(9–12):2899–2908

32. Sorger G, Sanikka T, Vilaça P, Santos TG (2018) Effect of processing temperatures on the properties of a high-strength steel welded by FSW. Weld World 62:1173–1185

33. Mahoney M, Rhodes CG, Flintoff JGP, Spurting RA, Bingel WH (1998) Properties of friction-stir-welded 7075 T651 aluminum. Metall Mater Trans A Phys Metall Mater Sci 29(7):1955–1964

34. Hwang Y, Kang Z, Chiou Y, Hsu H (2008) Experimental study on temperature distributions within the workpiece during friction stir welding of aluminum alloys. 48:778–787

35. Upadhyay P, Reynolds AP (2010) Effects of thermal boundary conditions in friction stir welded AA7050-T7 sheets. Mater Sci Eng A 527(6):1537–1543

36. Kadian AK, Puri G, Biswas P, Prediction of Thermal History of Friction Stir Welding by Considering Combined Stick and Slip Condition of AA1100 (AIMDR) 1–7 (2014)

37. Al-Badour F, Merah N, Shuaib A, Bazoune A (2013) Coupled Eulerian Lagrangian finite element modeling of friction stir welding processes. J Mater Process Technol 213(8):1433–1439

38. Lambiase F, Paoletti A, Di Ilio A (2018) Forces and temperature variation during friction stir welding of aluminum alloy AA6082-T6. Int J Adv Manuf Technol 337–346

39. Pew JW, Nelson TW, Sorensen CD (2007) Torque based weld power model for friction stir welding. Sci Technol Weld Join 12(4):341–347

40. Fratini L, Buffa G, Palmeri D et al (2006) Material flow in FSW of AA7075-T6 butt joints: Numerical simulations and experimental verifications. Sci Technol Weld Join 11(4):412–421

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