Journal of Materials Processing Technology 212 (2012) 2051–2057

Contents lists available at SciVerse ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Using torque sensitivity analysis in accessing Friction Stir Welding/Processing conditions

C. Leitão[a], R. Louro[b], D.M. Rodrigues[a,*]

[a] CEMUC, Mechanical Engineering Department, University of Coimbra, Portugal
[b] ISQ, Weld and Quality Institute, Portugal

A R T I C L E I N F O

Article history:
Received 27 February 2012
Received in revised form 8 May 2012
Accepted 16 May 2012
Available online 26 May 2012

Keywords:
FSW
Torque
Welding parameters
Materials properties

A B S T R A C T

The use of Friction Stir Processing (FSP) techniques for the joining and/or transforming of metallic materials is being object of intensive research since the earliest development of the Friction Stir Welding (FSW) technology in 1991. Despite of this, an accurate understanding of the main welding/processing mechanisms and its relation with the process parameters is still missing. Current paper intends to provide some further insight on this subject by discussing the relations between processing parameters, classified as independent variables, and the corresponding welding results, classified as dependent variables, using torque sensitivity analysis. The relation between base materials properties, plate thickness, welding conditions and torque evolution were also explored, which constitutes a novelty relative to the previous studies on this subject.

1. Introduction

Since its development in the nineties, the friction stir processing (FSP) techniques, such as Friction Stir Welding (FSW) and Friction Stir Surfacing (FSS), which were developed for joining and/or improving locally material properties by using solid state processing principles, are being developed and applied based on trial and error analysis for optimizing processing conditions. Actually, full understanding of FSW/P mechanisms and/or thermomechanical principles was not achieved yet, still missing important data relating process parameters and material properties with processing conditions and processed components mechanical and metallurgical characteristics. According to Colligan and Mishra (2008), such understanding should be helpful in deciding how to change process conditions to achieve desired effects, such as improving materials strength, eliminating weld/processing defects and transferring welding/processing procedures to new processing conditions and/or materials. Finding a process output parameter, enabling full control of processing conditions and insuring suitable welding/processing results, is also an important step in consolidating the widespread application of FSW/P techniques at the industrial level.

Recently, Longhurst et al. (2010) proposed the use of the spindle torque registered by the welding machines as a process control parameter for FSW, in alternative to the commonly used plunge depth or vertical force controlled setups. According to them, using torque control, it is possible to adapt easily the weld process to changing workpiece characteristics, since it provides a more suitable indicator of the tool depth into the workpiece than axial force. Pew et al. (2007) argue that registering the torque during welding, and using it for evaluating the heat input during the process, not only enables to avoid the difficult and time consuming task of setting thermocouples before welding, but also enables post-weld analysis of the temperature fields. Khandkar et al. (2003), for example, developed an extensive numerical study of temperature distributions and thermal histories during friction stir welding by using an input torque based thermal model.

Some studies on the evolution of the spindle torque, with different processing variables, are also available in the scientific databases. Meanwhile, Cui et al. (2010) observed that torque depends mainly on rotational and welding speeds, Peel et al. (2006) and Arora et al. (2009) reported that the torque is relatively insensitive to the welding speed, since this parameter does not affect the temperature field as much as the rotation rate. Actually, several other works, such as that reported recently by Jacquin et al. (2011), clearly show that the spindle torque continuously decreases with increasing tool rotation speed. In all these works, the decrease in torque with increasing rotational speed was related to the decreasing flow strength of the base materials at increasing temperatures. This conclusion also points for a strong relation between torque and base material characteristics, which still needs to be explored. Colligan and Mishra (2008) showed that the welding torque also

---

* Corresponding author. Tel.: +351 239 790 700; fax: +351 239 790 701.
E-mail address: dulce.rodrigues@dem.uc.pt (D.M. Rodrigues).

0924-0136/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jmatprotec.2012.05.009

Table 1
Welding parameters.

Alloy	Thickness [mm]		Process parameters		Tool parameters			
			v [mm min^{-1}]	ω [RPM]	D_s [mm]	D_p [mm]	α [°]	F_z [kN]
AA5083-H111	4 mm	Set1	300	400	13	5	1	7
			400	500	15	6	2	11
			500	600	18		3	15
		Set2	300–700	400–1100	15	6	3	15
	6 mm	Set1	200	300	15	6	1	10
			275	400	18	7	2	15
			350	500	21		3	20
		Set2	50–350	300–1000	21	7	3	20
AA6082-T6	3 mm	Set1	800	1000	10	4	1	5
			950	1150	12	5	2	7
			1100	1300	15		3	9
	6 mm	Set1	200	300	15	6	1	10
			275	400	18	7	2	15
			350	500	21		3	20
		Set2	200–1000	500–1000	21	7	3	20

depends on tool parameters, such as shoulder and pin dimensions. However, the range of welding conditions tested was so limited that this aspect still needs further research.

Actually, in spite of being well established the strong relation between torque and welding/processing conditions, all the studies reported to date are focused on a limited range of processing parameters, and most of them analyse results for a very specific material, tool geometry or plate thickness. Current paper intend to provide some further insight on this subject by discussing the relations between a broad range of processing conditions, classified as independent variables, and the corresponding welding results, classified as dependent variables, using torque sensitivity analysis. The welding conditions tested included not only testing varied processing parameters, which enabled to compare present data with previous studies from other authors, but also analysing the relation between base materials properties, plate thickness, welding results and torque evolution, which constitutes a novelty relative to the previous studies on this subject.

2. Experimental procedure

The two base materials used in this study were a non-heat-treatable AA5083-H111 and a heat-treatable AA6082-T6 aluminium alloy, each supplied in two different plate thicknesses: 6 mm and 4 mm, for AA5083-H111 alloy, which will be labelled as 5_6 and 5_4, respectively, and 6 and 3 mm, for the AA6082-T6 alloy, which will be labelled as 6_6 and 6_3, respectively. Bead-on-plate welds were produced in order to avoid any influence of sheet positioning and clamping on torque sensitivity analysis.

Tools with conical shoulders, with a cone angle of 5°, and cylindrical threaded pins, were used in all welding tests. Although the geometry was maintained, the tool dimensions, namely, the pin (D_p) diameter, shoulder (D_s) diameter and pitch angle (α) were varied. For each tool tested, the welding speeds (v), rotating speeds (ω) and vertical forces (F_z) were varied according to the values displayed in Table 1. Using the parameters identified as *Set1*, Taguchi analysis was performed in order to establish a testing plan for each base material and plate thickness, as described in Louro et al. (2010), which determined a total of 114 welding tests to be performed. After analysing *Set1* welding results, some supplementary tests were scheduled for both base materials (identified as *Set2*, in Table 1), in order to accomplish a more comprehensive analysis of their welding behaviour.

After welding, all welds were visually inspected for identifying defects such as flash and surface flaws. Transverse weld specimens were also prepared, cold mounted, polished, etched and observed using the Zeiss Stemi 2000-C and Zeiss Axiotech 100HD microscopes, for detecting large and very small internal flaws, as well as for analysing welds' morphology. Finally, using the FSW machine output data, the average torque values, for each welding test, were listed and analysed in relation to welding results.

3. Torque sensitivity analysis

3.1. Influence of plates thickness and process parameters

In Figs. 1 and 2 are plotted the average torque values versus the rotational to weld speed ratio (ω/v), corresponding to all welding tests performed for the AA5083 and AA6082 alloys, respectively. The results plotted in the figures are categorised according to the classification adopted after weld inspection: the welding conditions conducting to welds with no defects or very small defects, which were labelled as *GOOD*, are represented by large circles, and the welding conditions conducting to welds with defects, such as flash (*F*), surface flaws (*SD*) and internal voids (*ID*) are represented with smaller symbols, of different shapes, according to the defect type. Welding conditions, for which the pin was broken (*BP*), precluding the execution of the weld, are also identified. A detailed

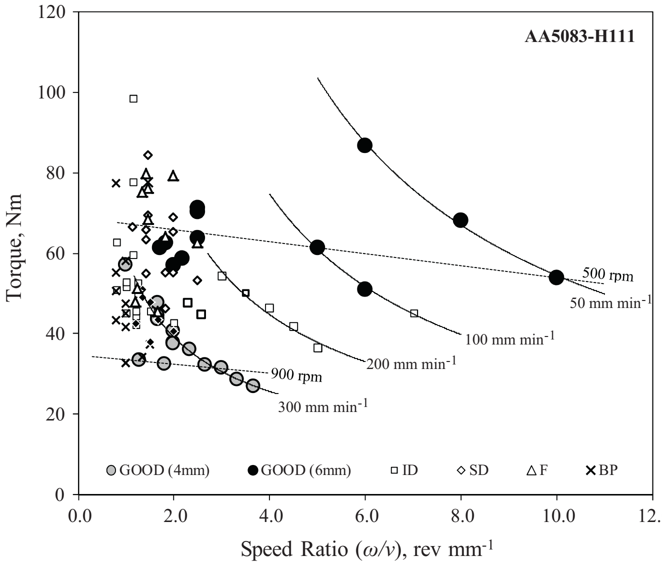

Fig. 1. Torque evolution with (ω/v) and weld inspection results for the AA5083 welds.