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The optimisation of process parameters for friction stir spot-welded AA3003-H12 aluminium alloy using a Taguchi orthogonal array

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ABSTRACT

The aim of the present work is to optimise the welding parameters for friction stir spot welded non-heat-treatable AA3003-H12 aluminium alloy sheets using a Taguchi orthogonal array. The welding parameters, such as the tool rotational speed, tool plunge depth and dwell time, were determined according to the Taguchi orthogonal table L9 using a randomised approach. The optimum welding parameters for the peak tensile shear load of the joints were predicted, and the individual importance of each parameter on the tensile shear load of the friction stir spot weld was evaluated by examining the signal-to-noise ratio and analysis of variance (ANOVA) results. The optimum levels of the plunge depth, dwell time and tool rotational speed were found to be 4.8 mm, 2 s and 1500 rpm, respectively. The ANOVA results indicated that the tool plunge depth has the higher statistical effect with 69.26% on the tensile shear load, followed by the dwell time and rotational speed. The tensile shear load of the friction stir spot welding (FSSW) joints increased with increasing plunge depth. Additionally, examination of the weld cross-sections, microhardness tests and fracture characterisation of the selected friction spot welded joints were conducted to understand the better performance of the joints. All the fractures of the joints during tensile testing occurred at stir zone (SZ), where the bonded section was minimum. The tensile shear load and tensile deformation of the FSSW joints increased linearly with increasing the bonded size. The finer grain size in the SZ led to the higher hardness, which resulted in higher fracture strength. When the tensile shear load of the joints increased approximately 3-fold, the failure energy absorption of the joints increased approximately 15-fold.

1. Introduction

The electrical resistance spot welding (ERSW) process is widely used in the joining of sheet metal assemblies due to its advantages in welding efficiency and suitability for automation [1,2]. Lightweight metal joints have experienced problems in ERSW, such as alloy element evaporation leading to property degradation, shorter electrode tip life, porosity, hydrogen cracking, flush, wear, overheating and melting. In 2003, the Mazda Motor Corp., Japan, announced that it had developed a spot welding method based on friction stir welding (FSW) for manufacturing aluminium body assemblies [3]. This technique has the same advantages as a solid-state welding process FSW, such as ease of handling, no welding cracking or porosity problems, superior weld mechanical properties, suitability for welding dissimilar materials, a reduction in the overall structural weight, low residual stress, low energy input and little waste or pollution compared with the conventional welding method [4].

The principle of FSSW is similar to that of FSW: Tool plunge, material mixing during dwell time and tool reaction [5]. A schematic illustration of the FSSW process is presented in Fig. 1. One difference is that there is no translation of the tool during FSSW [6,7]. Unlike FSW, FSSW can be considered a transient process due to its short cycle time [8]. In this process, welds are produced using a non-consumable tool, consisting of a pin and a shoulder. Typically, the pin length is selected such that it sufficiently penetrates into the lower sheet [4]. The process starts with spinning the tool at a high rotational speed. After the rotating tool is gradually plunged into the sheets in a lap configuration until the shoulder comes in contact with the upper sheet surface, the tool rotates for a few seconds without translation motion, which is the dwelling process. After a certain dwell time, the rotating tool is then retracted from workpieces, and the retraction of the pin leaves a characteristic exit hole [7,9–12]. The heat generated by the plastic dissipation within the workpieces stirred by the rotating tool as well as by the friction between the tool and workpieces softens

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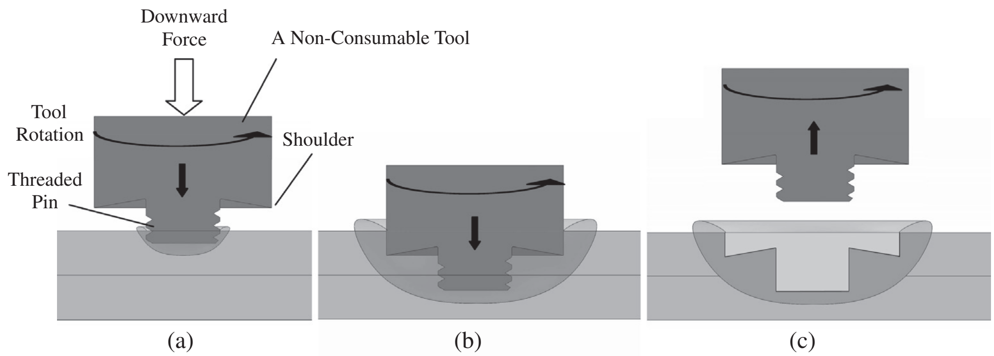

Fig. 1. A schematic illustration of the FSSW process: (a) plunging, (b) stirring (Dwell), (c) retracting.

the material being welded. The weld cross-sections of the FSSW joints reveal four main distinct microstructural zones analogously to the FSW process: SZ, thermo-mechanically affected zone (TMAZ), heat affected zone (HAZ) and base metal (BM) [4,9,13–17].

The tool rotational speed, dwell time and plunge depth are the most important process parameters that affect the mechanical properties of friction stir spot welded joints [18]. Many studies have focused on the effect of process parameters on the microstructure and mechanical properties of friction stir spot welds [1,4,9,15,18–21]. Gerlich et al. [18] investigated the effect of rotational speed (in the range of 750–3000 rpm) on the strain rates during friction stir welding of aluminium alloys. They stated that the calculated strain rate during spot welding decreased when the tool rotational speed increased from 750 to 3000 rpm. Additionally, they observed that the tool rotational speed of 3000 rpm did not alter the bonded size of weld region. Lathabai et al. [7] indicated that the tensile shear load of friction stir spot welded joints increased with increasing tool rotational speed up to a certain value, and then decreased with the further increase of tool rotational speed. Similarly, Yuan et al. also [22] reported that the tensile shear load of friction stir spot welded joint of an aluminium alloy sheet first increased and then decreased with increasing rotational speed from 1000 to 2500 rpm. Tozaki et al. [17] and Merzoug et al. [20] also found that the tensile shear load of friction stir spot welded joints decreased with increasing tool rotational speed. In general, higher rotational speed leads to the lower mechanical properties for a friction stir spot welded joints. This can be associated with the higher heat input with increasing tool rotational speed, which gives rise to the grain growth in the weld region of non-heat treatable aluminium alloys or the precipitate coarsening in the weld region of heat treatable aluminium alloys. However, Su et al. [23] stated that stir zones produced using rotational speeds below 750 rpm did not exhibit good bonded regions. This can be associated with the low heat input, which causes improper stirring action around the tool pin due to insufficient plasticization of the base metal under the tool shoulder. These welding conditions, such as low tool rotational speed and dwell time, produce defective welds.

Dwell time is also an effective parameter on the weld strength in friction stir spot welding process. Tozaki et al. [17] and Tran et al. [21] investigated the effect of dwell time on weld properties. Tran et al. [21] pointed out that the weld strength increased with increasing dwell time. Pathak et al. [24] also indicated that the tensile failure load of a friction stir spot weld increased when the dwell time was increased from 4 s. to 12 s. Higher dwell time produces higher frictional heat input, which leads to effective increase in bonded size during stirring. However, Arul et al. [25] stated that the tensile shear failure load of friction stir spot welded joint first increased and then decreased with increasing dwell time.

Plunge depth is another effective parameter on the weld strength in friction stir spot welding process. The effect of tool plunge depth on mechanical properties was studied by Merzoug et al. [20]. They reported that the mechanical properties of friction stir spot welded joints increased with increasing tool plunge depth. However, a deep plunge depth may lead to decreased weld strength due to excessive thinning of the top sheet. Additionally, Yuan et al. [22] stated that the high plunge depth made the hook tip upward, which can reduce the effective thickness of the upper sheet.

The non-heat treatable 3003 aluminium alloy has more strength than the 1100 aluminium alloy due to the alloying element Mn. This alloy has been widely used for moderate-strength applications requiring good workability, such as stampings, spun and drawn products, chemical equipment, storage tanks, fan blades, walkways, flooring, and truck and trailer components. Although there are various studies on the microstructures, mechanical properties and failure mechanisms of friction stir spot welded heat treatable aluminium alloys in the literature [4,7,16,21], only a few focused on friction stir spot welded non-heat treatable aluminium alloys. The database for mechanical properties of friction stir spot welded non-heat treatable aluminium alloys is relatively deficient. Additionally, no published results have been presented on the optimisation of process parameters of friction stir spot welded non-heat-treatable 3003 aluminium alloys. The aim of the present work was to determine the optimum process parameters and to estimate the contribution of the individual process parameters to the tensile shear load of the friction stir spot welded 3003 aluminium alloy using the Taguchi orthogonal array, which is a powerful statistical tool that is often used in industrial process optimisation and analysis. The Taguchi method can be applied to the design of high quality systems without increasing costs, and this method enables an understanding of the effect of individual and combined process parameters from reduced experimental tests [19]. In addition, the microhardness values in the different weld zones, microstructural changes, and failure characteristics of the selected friction stir spot welds were discussed to offer explanations for the better performance of the joints.

2. Experimental details

The present study was performed on rolled sheets of AA3003-H12 aluminium alloy with a thickness of 3 mm. Its chemical composition is of 0.201% Si, 0.665% Fe, 0.053% Cu, 1.082% Mn, 0.127% Mg, 0.014% Zn, 0.021% Ti, 0.011% Ga, 0.018% V, balance Al (all compositions are in wt%). Two aluminium sheets with dimensions of 140 mm $\times$ 40 mm were friction stir spot welded in the overlapping configuration using a vertical CNC milling machine with a constant 50 mm/min plunging feed and drawing out speed (Fig. 2). A FSW nonconsumable tool made of H13 hot work tool steel with a 10°