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Microstructural features and mechanical properties of AM60 and AZ31 friction stir spot welds

Y.H. Yin [a,*], A. Ikuta [b], T.H. North [c]

[a] School of Material Science and Engineering, Tianjin University, Tianjin 300072, China
[b] Department of Mechanical Engineering, School of Engineering, Kinki University, Hiroshima 739-2116, Japan
[c] Department of Materials Science and Engineering, University of Toronto, Toronto, ON, Canada M5S 3E4

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ABSTRACT

The microstructural features and mechanical properties of AM60 and AZ31 friction stir spot welds are investigated in joints made using different tool designs (threaded and three-flat/threaded tools) and dwell time settings. Since the hook regions are curved inwards towards the keyhole periphery in AM60 friction stir spot welds made using threaded and three-flat/threaded tools and different dwell time settings, the distance from the tip of the hook region to the keyhole periphery mainly determines their failure load properties. In contrast, the hook regions are curved outwards from the axis of the rotating tool in AZ31 friction stir spot welds and their failure strength properties are determined by the bonded width, the distance from the tip of the hook region to the sheet intersection, the depth of tool shoulder penetration into the surface of the upper sheet and the distance from the tip of the hook region to the top of the welded joint.

The highest failure load properties are found in AM60 friction stir spot welds made using a three-flat/threaded tool and dwell times of 3 and 4 s, since the distance from the tip of the hook region to the keyhole periphery is highest in these joints. The highest failure load properties are found in AZ31 friction stir spot welds made using the three-flat/threaded tool and a dwell time of 1 s, since these joints have the largest bonded widths, distances from the tips of the hook regions to the sheet intersection, and limited penetration of the tool shoulder into the surface of the upper sheet (about 0.5 mm).

1. Introduction

The Friction Stir Welding (FSW) process was developed by TWI in 1991 [1] as a novel method for joining Al-alloys and, since that time, the welding process has been employed when fabricating non-ferrous alloys (aluminum, titanium, magnesium, zinc and copper alloys), as well as steel and thermoplastic substrates having thicknesses from 1 to 50 mm. Friction stir spot welding is a process variant of friction stir seam welding where joints are made at a particular location by plunging and retracting a rotating tool into and out of lapped sheets.

The influence of welding parameters on the failure load properties of Al-alloy friction stir spot welds has been examined at length [2–12]. Improved joint strength properties are produced when high axial force values in combination with high tool rotational speed and short welding time settings are used [2]. Increasing energy input and bonded area have also been associated with higher joint strength properties [3]. It has also been suggested that joint failure load properties increase and then decrease when the cycle time and tool rotational speed are increased [6]. Although Tozaki et al. [8] and Lathabi et al. [9] have suggested that the failure load properties are improved when the depth of penetration of the rotating tool into the adjoining sheets increases, quite different results were found by other investigators. For example, Freeney et al. [11] and Mitlin et al. [12] reported that increasing penetration depth had no influence on failure load properties. Tool geometry also has an important influence on the failure load properties of friction stir spot welds. For example, the failure load properties of Al 5083 [13,14] and AZ31 [15] friction stir spot welds are improved when a triangular-shaped tool is used, while the use of a new scroll-grooved tool design produces much higher failure strength properties [16].

In addition, the failure load properties of friction stir spot welds are markedly influenced by the dimensions and curvatures of the partially-bonded regions formed during joining. Partially-bonded regions are created when the oxidized surfaces of the contacting sheets are brought into intimate contact at the joint extremity; they are commonly referred to as hook regions, since they have curved profiles [17–19].

It is well documented that the overlap shear strength properties of adhesively-bonded substrates result are improved when the

* Corresponding author. Tel.: +86 416 978 5875; fax: +86 416 978 4155.
E-mail address: yinyuhuan@tju.edu.cn (Y.H. Yin).

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overlap length increases [20,21]. With this in mind, it has been recently suggested that friction stir spot welds will have the highest failure load properties when they have large bonded widths, the ratio of the distance from the sheet intersection to the tip of the hook region (v) divided by the initial sheet thickness (t) is small and the hook region is curved outwards from the axis of the rotating tool [15]. The bonded width comprises the stir zone width, the width of lower sheet material displaced upwards during friction stir spot welding and the width of the partially-bonded region at the hook region. This line of approach works particularly well when the failure load properties of AZ31 friction stir spot welds made using a wide range of tool rotational speed and plunge rate settings are examined, since the hook regions formed during friction stir spot welding are curved outwards from the axis of the rotating tool [15].

However, it is confirmed in the present paper that the hook regions formed during AM60 friction stir spot welding are not curved outwards from the axis of the rotating tool; instead, they are curved inwards towards the keyhole periphery. As a result, a quite different line of approach is needed when analyzing the failure load properties of AM60 friction stir spot welds. The influence of tool geometry and dwell time settings on the failure load properties of AM60 friction stir spot welds is investigated. The failure load properties of AM60 friction stir spot welds are compared with those found during overlap shear tests of AZ31 friction stir spot welds made using identical welding parameter settings.

2. Experimental procedure

All friction stir spot welds were made using 1.5 mm thick AZ31 and AM60 sheets. The as-received AM60 sheet had a microstructure comprising α-Mg grains and $Mg_{17}Al_{12}$ located at inter-dendritic boundaries; see Fig. 1. The wrought AZ31 sheet had a microstructure comprising fine α-Mg grains having an average grain size of 9 μm. Since the stir zone profile and the upward displacement of lower sheet material during the friction stir spot welding operation is readily discernible in joints made between upper and lower sheets having widely different average grain sizes, a number of AZ31 and AM60 sheets were heat-treated for 48 h at a temperature of 415 °C in an argon atmosphere followed by water-quenching. The average grain sizes of heat-treated AM60 and AZ31 sheets were 21 and 48 μm. In friction stir spot welding trials where heat-treated AZ31 and AM60 sheets were used, they were always the lower sheet in the sandwich.

The displacement-controlled friction stir spot welding machine used during this investigation has been described in detail elsewhere [22,23]. Two tool designs were employed during friction stir spot welding, namely: a tool with a cylindrical pin and an M4 thread and a three-flat/threaded tool. The tool shoulder diameter was 10 mm, the pin diameter was 4 mm and the pin length was 1.8 mm. The tool rotational speed was 2250RPM, the plunge rate was 2.5 mm s^{-1} and the dwell time ranged from 0 to 4 s during all AM60 and AZ31 friction stir spot welding trials.

The locations of the tips of hook regions relative to the keyhole periphery and the top of the AM60 and AZ31 friction stir spot welds were determined using optical microscopy (at 1000× magnification). The stir zone and bonded widths, the depth of penetration of the tool shoulder into the surface of the upper sheet, the angle of curvature of hook region and the distance (Y) from the tip of the hook region to the keyhole periphery were measured from transverse microsections. The errors in estimating the bonded width, the height of the tip of the hook above the sheet intersection, the distance (Y) from the tip of the hook region to the keyhole periphery and the depth of tool shoulder penetration into the surface of the upper sheet were ±10 μm for any reported value. The angle of curvature of any hook region was determined by drawing

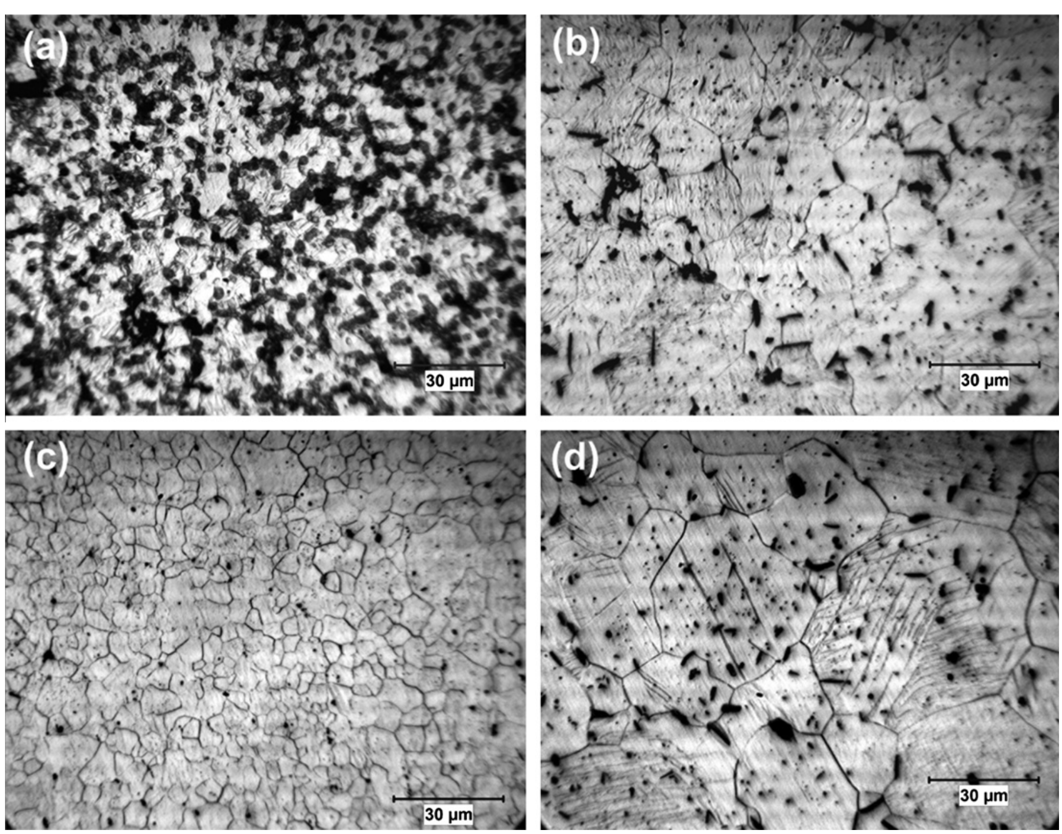

Fig. 1. Microstructural features of (a) as-received and (b) heat-treated AM60 sheet, (c) as-received and (d) heat-treated AZ31 sheet.