Journal of Materials Processing Technology 225 (2015) 393–404

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Dissimilar joining of aluminum alloy and stainless steel thin sheets by thermally assisted plastic deformation

Zhequn Huang[a,*], Jun Yanagimoto[b]

[a] Graduate School of Engineering, The University of Tokyo, Komaba 4-6-1, Meguro, Tokyo 153-8505, Japan
[b] Institute of Industrial Science, The University of Tokyo, Komaba 4-6-1, Meguro, Tokyo 153-8505, Japan

ARTICLE INFO

Article history:
Received 22 December 2014
Received in revised form 18 June 2015
Accepted 20 June 2015
Available online 24 June 2015

Keywords:
Aluminum–steel dissimilar joining
Plastic deformation
Mechanical anchoring
Diffusion bonding
Interdiffusion layer

ABSTRACT

Aluminum alloy/steel hybrid components are widely used in different industrial areas because of their high performance. However, the high importance of reducing the thickness of components to realize lightweight products requires the dissimilar joining of Al alloy and steel thin sheets (less than 1 mm in thickness), which is a major challenge using current joining technologies. In this paper, an alternative dissimilar joining process by thermally assisted plastic deformation is proposed for thin metallic sheets. The effects of various parameters on the joining performance were investigated. After exposure to an elevated temperature of 450 °C for 22 s, an optimized joint type was achieved by local plastic deformation using a punch-die pair. This joint type exhibited an average joint efficiency factor of 85.2%, and an average absorption energy of 1.69 kN mm in tensile shear tests, as well as satisfactory joining performance in peel tests. In addition to mechanical anchoring and surface enlargement, atomic interdiffusion at the interface activated by the elevated forming temperature was found to be critical for obtaining high joining quality. The thickness of the Fe-Al interdiffusion layer at the interface was positively correlated with the heat input and the locally distributed plastic strain. This study shows that the proposed dissimilar joining process for Al alloy and steel thin sheets is a promising joining method for Al alloy/steel lightweight structures owing to the excellent joining performance, weight effectiveness, simple operation and long tool lifetime.

1. Introduction

The emerging requirements of higher structural performance with lower weight and energy consumption in the aerospace, automobile, electrical, and chemical industries are stimulating the rapid development of lightweight structures. Steel alloy has good creep resistance and formability as well as relatively high strength, while Al alloy possesses low density and excellent corrosion resistance. In recent years, Al-steel hybrid structures have been widely used in lightweight products. Although dissimilar joining between steel and Al alloy has been investigated intensively, achieving satisfactory joining quality remains a technological challenge owing to the distinct differences between the two dissimilar materials, such as thermal expansion coefficient, melting temperature, mechanical properties, *etc.*, as well as the ease of formation of brittle intermetallic compounds (IMCs) at the interface during the welding process.

Various thermal welding processes have been proposed for joining Al alloy to steel, such as resistance spot welding, laser welding, laser braze welding and laser rolling welding, which were respectively utilized by Connolly (2007), Torkamany et al. (2010), Sierra et al. (2008) and Ozaki and Kutsuna (2012). However, the existence of microvoids and thick brittle IMCs could not be avoided, which would degrade both the static and fatigue joining performance. The recently developed friction stir welding (FSW) process is another joining process which involves plastic deformation. As reviewed by Mishra and Ma (2005), during FSW process, heat is generated by friction between a rotating tool and the workpieces. The softened and severely plastic-deformed base material is transported from the tool front to the trailing edge and then quickly forged into a joint. FSW has a smaller heat-affected zone and better joining performance than other welding technologies and has been regarded as a promising joining approach for dissimilar sheets. An improved hybrid welding process combining gas tungsten arc welding and FSW was proposed by Bang et al. (2012), which was used to join 3-mm-thick Al alloy to 3-mm-thick SUS304 sheets with a high

* Corresponding author. Fax: +81 354526204.
E-mail addresses: hzhequn@iis.u-tokyo.ac.jp, huangzhequn@gmail.com (Z. Huang).

http://dx.doi.org/10.1016/j.jmatprotec.2015.06.023
0924-0136/

Table 1
Chemical composition of 0.8-mm-thick A6061P-T6 sheet (wt%).

Element	Mg	Si	Fe	Cu	Cr	Zn	Mn	Ti	Al
% wt	0.5–1.2	0.4–0.8	0.7 Max	0.15–0.4	0.04–0.35	0.25 Max	0.15 Max	0.15 Max	Bal.

Table 2
Chemical composition of 0.5-mm-thick SUS304 sheet (wt%).

Element	Cr	Ni	Mn	Si	C	P	S	Mo	Fe
% wt.	18.0–20.0	8.0–10.5	2.0 Max	1.0 Max	0.08 Max	0.045 Max	0.03 Max	–	Bal.

joint efficiency factor of approximately 93%. However, the penetration and rotation of the pin in the base materials would result in microvoids along the interface and a short tool lifetime. Additionally, micrometer-thick brittle IMCs were also easily formed at the bonding interface during the direct intermixing, which would deteriorate the fatigue joining strength according to Briskham et al. (2006). More importantly, as far as ultrathin metallic sheets are concerned, dissimilar joining by FSW is a major challenge as the penetration of the rotating tool would easily induce severe defects in thin sheets.

Conventional mechanical fastening is the main method used to assemble Al alloy and steel sheets. However, it usually induces stress concentration at the connection, decreases the corrosion resistance and requires a predrilled hole and an additional component such as a bolt, screw or rivet. Self-piercing riveting (SPR) and mechanical clinching, which are two typical joining processes by plastic deformation, have been attracting increasing interest in recent years, as reviewed by Mori et al. (2013) and Groche et al. (2014). An SPR joint is achieved through directly piercing sheets with a rivet at room temperature without the need for a predrilled hole. The SPR process has been utilized by Abe et al. (2009) to join Al alloy to steel sheets. However, its applicability is limited to thicker sheets because rupture and fracture are difficult to avoid in the riveting of ultrathin sheets (*e.g.*, 0.5 mm in thickness). Mechanical clinching is a low-noise cold joining process in which the metallic sheets are locally deformed by a rigid punch-die pair without using an additional element or a predrilled hole. Its technical difficulties include forming interlock and avoiding fractures and cracks after deformation. Abe et al. (2012) investigated the applicability of the clinching process to Al alloy and high-strength steel and improved the joining performance by adapting the geometry of the tool and controlling the material flow. Nevertheless, the mechanical clinching process is less effective for very thin sheets owing to their poor ductility and formability at room temperature. Abe et al. (2012) also reported that when the thickness of the lower sheet was less than 1 mm, the crucial interlock could not be successfully formed, which was attributed to the insufficient material flow between the corners of the punch and the die.

Therefore, it is necessary to develop more reliable and effective dissimilar joining methods for Al alloy and steel thin sheets (less than 1 mm in thickness) for special lightweight requirements. In this study, we propose a new joining process by thermally assisted plastic deformation that combines mechanical and diffusion bonding techniques for thin metallic sheets, taking 0.8-mm-thick Al alloy and 0.5-mm-thick steel sheets as examples. Different from the conventional clinching technology, the proposed joining process does not aim at forming an interlock by severe plastic deformation owing to the limited formability of thin metallic sheets. The depth of the die is relatively low and the forming process is stopped at an intermediate stage of the conventional clinching process to avoid the occurrence of fractures and cracks in the joint. After plastic deformation, the two thin sheets are firmly pressed into the die cavity; thus, the relative movement of the sheets is effectively inhibited and the overall contact area is enlarged. In addition, induction heating is introduced to increase the ductility of the thin sheets, provide sufficient material flow and allow atomic interdiffusion between the dissimilar materials.

In the present work, the effects of the experimental parameters and tool geometry on the static tensile shear strength and peel strength of a single-lap joint were investigated. The failure modes of different joint types, the main joining mechanisms and the dependence of the joining performance on the forming temperature and plastic strain were also discussed.

2. Experimental procedure

2.1. Materials and experimental setup

0.8-mm-thick precipitate-hardened Al alloy (A6061P-T6) and 0.5-mm-thick stainless steel (SUS304) sheets were used to fabricate dissimilar joints in this study. The chemical compositions of these two metallic sheets are given in Tables 1 and 2, respectively, and their mechanical properties are presented in Table 3. The sheets were cut into pieces of size of 26 mm (W) × 32 mm (L). Neither type of metallic sheet was subjected to any surface treatment. The A6061P-T6 sheet was placed above the SUS304 sheet with an overlapping area of 26 mm (W) × 26 mm (L).

The dissimilar joining process by thermally assisted plastic deformation was conducted in air using a 5 t high-precision compression machine. A simplified schematic of the experimental setup for the joining process is shown in Fig. 1(a). A spring was utilized to provide the blank holding force. In the cases of dissimilar joining at elevated temperatures, the specimens were heated by an induction coil unit to target temperatures of 150, 300, 350, 400, and 450 °C at the same heating rate of 15 °C/s using a thermocouple-based sensor-feedback system. After the target temperature was reached and maintained for approximately 10 s, the punch moved downward with a stroke of less than 2.0 mm. The punch was then pulled out of the connection, and the specimen was cooled in air. The heating history and the forming procedure are presented in Fig. 1(b).

Table 3
Mechanical properties of the used metallic sheets.

Sheet	Thickness (mm)	Density (g/cm^3)	Young's modulus (GPa)	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Poisson's ratio
A6061P-T6	0.8	2.7	68.9	310	276	12	0.33
SUS304	0.5	8.0	190	520	240	45	0.29