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Influence of tool pin design on properties of dissimilar copper to aluminum friction stir welding

Kush P. MEHTA, Vishvesh J. BADHEKA

Department of Mechanical Engineering, School of Technology, Pandit Deendayal Petroleum University, Raisan, Gandhinagar 382007, India

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Abstract: Dissimilar friction stir welding (FSW) of copper and aluminum was investigated by nine different tool designs, while the rest of the process parameters were kept constant. Mechanical and metallurgical tests such as macrostructure, microstructure, tensile test, hardness, scanning electron microscope and electron X-ray spectrographs were performed to assess the properties of dissimilar joints. The results exhibited that, the maximum joint strength was achieved by the tool of cylindrical pin profile having 8 mm pin diameter. Besides, the fragmental defects increased as the number of polygonal edges decreased, hence the polygonal pin profiles were unsuitable for dissimilar FSW butt joints. Furthermore, the tensile strength increased as the number of polygonal edges increased. Stir zone of polygonal pin profiles was hard and brittle relative to cylindrical tool pin profiles for same shoulder surface. Maximum hardness of HV 283 was obtained at weld made by the polygonal square pin profile. The hard and brittle intermetallic compounds (IMCs) were prominently presented in the stir zone. Phases of IMCs such as CuAl, $CuAl_2$, Cu_3Al and Cu_9Al_4 were presented in the stir zone of dissimilar Cu−Al joints.
Key words: Cu−Al joint; dissimilar friction stir welding; pin profiles; properties; intermetallic

1 Introduction

Joining of dissimilar materials such as copper (Cu) and aluminum (Al) is economically advantageous, and in addition yields exceptional mechanical, thermal and electrical properties [1]. Welding of these materials is challenging because of difference in its melting temperature, chemical compositions, physical properties and flow stress that in turn lead to the defects such as residual stresses, cracking and formation of large amount of brittle intermetallic compounds (IMCs) [1,2]. Although, solid state processes are potential techniques to join Cu−Al materials [2]. Friction stir welding (FSW) is an advance technology that falls under the category of solid state processes, and is reliable in dissimilar joints. As the name implies, friction as well as stirring action form the weld through non-consumable rotating tool having specially designed shoulder and pin, leading to sound joint [3]. The important elements of FSW tool are material of pin and shoulder, shoulder to pin diameter ratio, pin geometries, pin length, shoulder features and individual diameters of pin and shoulder. Variations in these elements consequently influence the heating, plastic deformation, axial load, torque and material flow of welding [1−5].

In the available literatures, most of the research works have been carried out to elucidate the effects of process parameters such as rotational speed [1,6,7], welding speed [1,8,9], tool pin offset [1,7,10], workpiece material positioning [1,7] and tilt angle [11] on the properties of dissimilar Cu−Al FSW. Apart from these parameters, the tool design significantly affects the joint properties of dissimilar FSW [2,12,13]. However, the studies on tool design for Cu−Al FSW system are limited. AKINLABI et al [12] showed that the shoulder diameter influences the heat generation and material flow of dissimilar C11000-AA5754 FSW system that subsequently affects properties as well as the formation of IMCs. Additionally, they obtained acceptable joint properties by shoulder diameters of 15 and 18 mm relative to 25 mm. GALVÃO et al [13] concluded that the shoulder geometry strongly influences the material flow and the formation of IMCs in dissimilar Cu−Al materials. They recommended concave shoulder profile for dissimilar Cu−Al FSW system. MEHTA et al [2]

Corresponding author: Kush P. MEHTA; Tel: +91-8140009588; E-mail: kush_2312@yahoo.com; vishvesh79@gmail.com
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recommended cylindrical tool pin profile instead of tapered profile for dissimilar Cu−Al FSW system. Moreover, they reported that an increase in shoulder diameter leads to higher plunge load with sufficient heat which helps to eliminate internal joint defects.

Besides, the tool pin design significantly influences the properties of different friction stir welding and processing (FSW/P) regions (see Table 1). Furthermore, the polygonal pin profiles have an important role to change the properties of FSW/P region. The square tool pin profile produces better properties due to its pulsating effect for the similar FSW systems. To the best of the author's knowledge, investigations on tool pin design for dissimilar Cu−Al system are limited hitherto. Therefore, it is worthwhile to study the influence of pin designs on the properties of dissimilar Cu−Al FSW system. The influence of different pin profiles, including triangular, square, hexagonal and cylindrical along with different pin diameters on the properties of dissimilar FSW was elucidated.

Table 1 Summary of tool pin profiles for different FSW/FSP systems

Process	System and work piece material	Pin design/ profiles	Remarks/ Recommended pin design	Ref.
FSW	AA5083	Square and cylindrical	Square profile produces finer grain structure and higher tensile strength due to eccentricity, larger stir zone and higher temperature	[14]
FSW	Pure copper	Triangular, square, pentagonal and hexagonal	Square pin profile gives better mechanical properties due to more pulsating effect with 1.56 dynamic to static ratio	[15]
FSW	Al−10%TiB_2 metal matrix composite	Square, hexagonal, octagonal, tapered square and tapered octagonal	Straight square pin profile provides better mechanical properties	[16]
FSW	Dissimilar AA5083-H111 and AA6351-T6	Square, hexagonal and octagonal	Square pin gives highest tensile strength	[17]
FSW	Dissimilar AA5052-H32 and HSLA steel	Conical and cylindrical	Lesser taper angle 10° produces maximum tensile strength	[18]
FSW	AZ31B Mg	Cylindrical, taper, threaded cylindrical, square, triangular	Threaded cylindrical pin provides highest tensile strength	[19]
FSW	Dissimilar AZ31Mg and steel	Pin length variations	Shorter pin length gives better tensile properties	[20]
FSW	Dissimilar AA6082−AA7075	Square conical and conical with two groves	Square frustum conical pin profiles uniform material mixing	[21]
FSW	AZ31B-H24 Mg	Cylindrical pin (left hand thread and right hand thread orientation)	Left hand thread orientation produces superior properties	[22]
FSW	AA7020-T6	Cylindrical and chamfered shouldered frustum shaped pin	Chamfered shoulder having a frustum shaped rounded end pin produces a better quality weld	[23]
FSW	AA7075-T6	Conical and square	Conical pin results are better than square in terms of properties	[24]
FSW	Dissimilar AA6061-T651 and electrolytic tough pitch copper	Cylindrical and tapered pin	Cylindrical pin provides better dissimilar joint	[2]
FSP	AA2219	Cylindrical, threaded cylindrical, square and triangular	Square pin profile produces better properties	[25]
FSP	AA6061	Cylindrical, threaded cylindrical, square and triangular	Square pin profile produces superior properties	[26]
FSP	AA6061	Cylindrical, threaded cylindrical, square, tapered cylindrical and triangular	Square pin generates good quality FSP region	[27]
FSP	AA2219	Cylindrical, threaded cylindrical, tapered cylindrical, square and triangular	Square pin generates excellent properties	[28]
FSP	AA6061	Cylindrical, threaded cylindrical, tapered cylindrical, square and triangular	Square pin generates excellent properties	[29]