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Effects of tool pin design on formation of defects in dissimilar friction stir welding

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Abstract

Friction stir welding is an automatic process, falls under the category of solid state welding processes. In this study, friction stir welding was carried out on dissimilar copper to aluminum materials by nine different tool designs. Present investigation provides an insight on formation of defects under the effect of different tool pin designs. The tool pin profiles such as cylindrical, triangular, square and hexagonal were used in the present experimental investigation by keeping other parameters constant. These tool pin profiles were designed based on its static and dynamic constant areas from best suitable cylindrical profile. Besides, the defects were analyzed through visual observation, macrostructure, microstructural investigation and scanning electron microscope. The results revealed that, the copper particles detached from base material were large and irregular in case of polygonal pin designs. Maximum irregular and large copper particles were reported in welds made by triangular pin profiles. Additionally, polygonal pin profiles were generating defects such as voids, tunnel, cracks and fragmental defects irrespective of its static and dynamic constant areas. Furthermore, defects were decreased as the polygonal edges increases. Defect free macro joint was reported for cylindrical tool pin profile.

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Keywords: defects; dissimilar; friction stir welding; tool pin design

Nomenclature

Al	Aluminum
Cu	Copper
FSW	Friction stir welding
IMCs	Intermetallic compounds
Mg	Magnesium
PD	Pin diameter
Ti	Titanium
SEM	Scanning electron microscope

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1. Introduction

Friction stir welding is a solid state automatic process in which the joining is being done by specially designed non consumable rotating tool [1]. The tool consists of elements such as pin and shoulder that is rotated and travelled at certain speeds, which subsequently produces plastic deformation due to intense friction under the shoulder. The deformed material inside the shoulder is swirled by pin and lead to the joint as tool is traveled [1, 2]. Hence, the tool pin profiles affect material flow, plastic deformation and temperature variation that consequently influences the properties of the joint [1]. Different tool pin profiles such as cylindrical, triflute, trivex, conical, triangular, square, pentagonal, hexagonal, octagonal, thread-less and with threads have been reported in the literatures for different FSW systems [1]. Optimum pin profile depends on types of materials and variations in thicknesses. Different materials such as Al, Cu, Ti, Mg, steel and plastics can be welded by FSW [1, 2].

Dissimilar materials are widely applied in different sectors of industries such as electrical, chemical, nuclear, aerospace and petrochemical, because, benefits of its individual properties can be obtained [3-6]. However, the joining of dissimilar materials is difficult task due to enormous differences in its physical, chemical, mechanical and metallurgical properties [2, 3]. FSW is a feasible process to joint dissimilar materials such as Cu-Al, steel-Al, Ti-Al and Cu-steel because of its solid state nature [2, 3]. Its solid state nature also eliminates defects of fusion welding such as porosity, solidification cracking and generation of large amount of IMCs. Formation of IMCs generally found in dissimilar materials welded through fusion welding processes which subsequently reduces the properties of joint [2, 3].

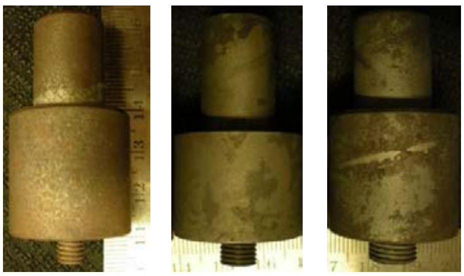
Dissimilar materials like Cu-Al have special properties such as good thermal and electrical conductivities [4-7]. Therefore, it can be applied for applications such as bus-bars, connectors, foil conductors of transformers, windings of capacitors and condensers, refrigeration and heat-exchangers tubes, etc [3]. At present, many researchers are performing research on Cu-Al FSW. Most of the available articles of this system elucidate the effect of process parameters on properties of joint [3-5, 7-12]. Some papers are also covering IMCs mechanisms and its influences on mechanical properties [13-17]. It has been found that, very few articles are available in the area of influence of tool design on formation of defects for dissimilar Cu-Al FSW system. The defects formation is major factor in dissimilar joints because of its differences in properties [3, 18, 19]. Defects such as cracks and voids generally occur due to fragments of Cu particles [3, 18, 19]. Additionally, defects such as tunnel defects, kissing bond, oxide entrapment, pores and flash effect were reported in FSW technology due to imbalance in parameters [3, 18, 19]. FSW tool plays a major role to obtain quality join [5, 6, 14]. It is mandatory to see the effect of tool design on formation of defects in dissimilar FSW system. Therefore, in the present study, the effects of polygonal tool pin profiles along with different cylindrical pin designs on formation of defects were investigated in dissimilar Cu-Al FSW.

2. Experimental procedure

AA 6061-T651 and electrolytic tough pitch Cu materials of 6.3 mm thickness were used to make butt type join via friction stir welding technology. Chemical compositions of these materials are mentioned in Table: 1. There were nine different tool designs used in this experimental study, which were made up from tool steel of M2 grade (see Table: 2 for chemical compositions). Experimental part was divided into three set of experiments wherein cylindrical tool pin profiles were used in first set of experiments. Pin diameters were varied as 6 mm, 8 mm and 10 mm by keeping remaining all parameters constant in case of first set of experiment (see Fig: 1).

Table: 1. Chemical compositions of base materials

Base Materials	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Impurities	Al	
AA 6061-T651	0.56	0.30	0.17	0.12	1.03	0.11	0.08	0.03	0.04	Balance	-
Electrolytic tough pitch copper	-	-	>99.9	-	-	-	-	-	Balance	-	97.15% Conductivity



(a) (b) (c)

Fig: 1 cylindrical tool pin profiles; (a) PD: 6 mm, (b) PD: 8 mm and (c) PD: 10 mm

(a) (b) (c)

Fig: 2 polygonal tool pin profiles: constant static volume covered by pin (a) triangular, (b) square and (c) hexagonal

Fig: 3 polygonal tool pin profiles: constant dynamic volume covered by pin (a) triangular, (b) square and (c) hexagonal

The second and third sets of experiments were performed by polygonal pin designs that were designed based on its static and dynamic constant volumes. The static and dynamic volumes of pin were kept at 326.43 mm^3 based on 8 mm diameter cylindrical tool pin profile. Here, these volumes were calculated based on results of first set of experiment. Polygonal tool pin profiles such as triangular, square and hexagonal were chosen for these experiments (refer Fig: 2 and Fig: 3). Furthermore, the welded samples were first checked visually, and then, that were further subjected to macro and microstructure analysis to identify defects. Microstructural analysis was done on metallographic samples that were mechanically grinded and polished on 120, 320, 800 and 1000 grit silicon carbide followed by etching through solutions such as FeCl + HCl + H_2O at Cu side and 100 % H_2O + 1 g NaOH at Al side. These solutions were swabbed on transverse cross section of the specimens individually. These samples were subjected for SEM to identify micro-level defects.

Table: 2. Chemical compositions of tool material

Elements	C	Cr	V	W	Mo	Co	Cb
Percentage (%)	0.80	4.00	2.00	6.00	5.00	-	-

3. Results and discussion

Visual examinations of cylindrical pin profiles are shown in Fig: 4. It can be seen that, throughout surface tunnel was observed in case of weld made by PD: 10 mm (Fig: 4 c, d and e). The cold conditions were observed on the surface as shown in Fig: 4 (d) and (e). Here, the shoulder had covered less area because of large pin diameter. It was obvious to have cold condition due to less area covered by shoulder that resulted in surface tunnel defect [2, 3, 5]. Besides, the flash effect was produced on the surface of weld made by PD: 6 mm (refer Fig: 4 a). This was hot condition in which the material was highly deformed and extruded out-side, that consequently resulted in flash effect [3]. However, defect free surface was reported in case of weld of PD: 8 mm as shown in Fig: 4 (b). Cross sectional views of weld made by tool having PD: 6 mm are shown in Fig: 5. It can be seen that big size pore was observed at the bottom of the weld which was found throughout the weld. Aforementioned conditions have extruded material out-side instead of pushing inside, which have restricted vertical flow of the material inside the shoulder and finally, the big sized pore has formed [3-5].

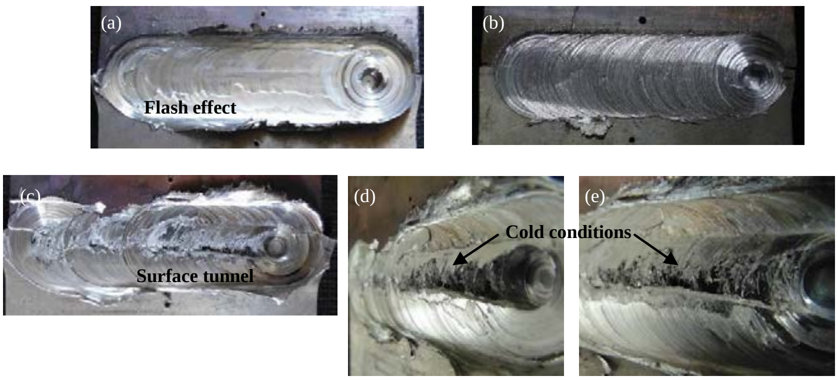


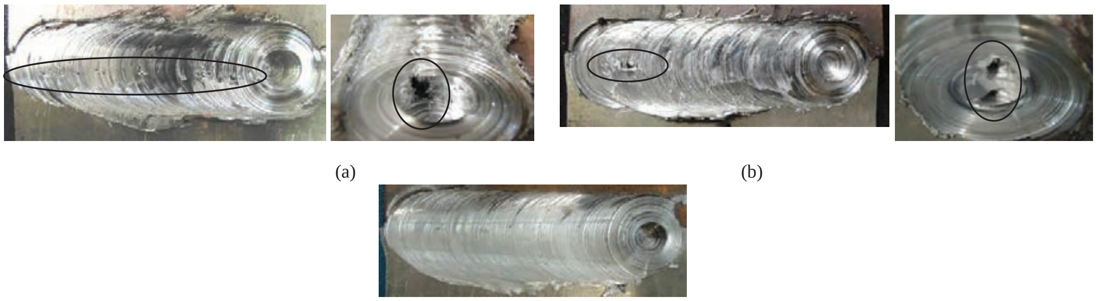
Fig: 4 visual observation of welds by cylindrical tool pin profiles; (a), PD: 6 mm (b), PD: 8 mm and (c, d, e) PD: 10 mm

(a) (b) (c)

Fig: 5 cross section view of welds made by tool having PD: 6 mm (a) macrostructure, (b) microstructure and (c) SEM image

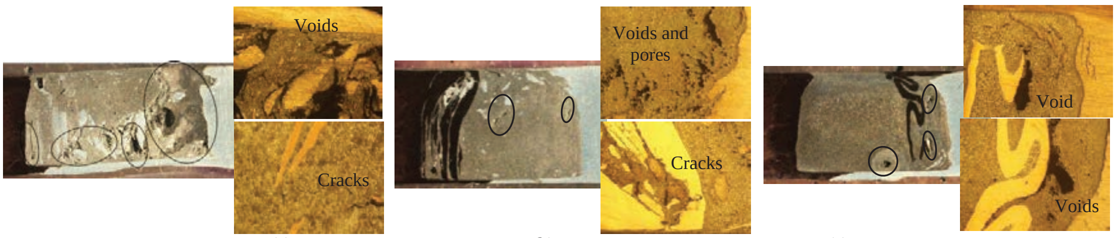
In the second set of experiment, the polygonal pin designs such as triangular, square and hexagonal profiles were used therein the static volume covered by the pins was kept constant for all. Hence, the pin volumes were different during operation as the static and polygonal volumes of polygonal pins can't be same. The visual examinations of the second set of experiment are shown in Fig: 6. Lack of surface fill was reported on the surface of weld produced by triangular pin profile while big sized pore was observed at the area of key-hole (see Fig: 6 a). Same type of defects was reported in the weld of square pin profile (see Fig: 6 b). The reason behind these defects was inadequate pressure placed onto the work piece materials. Inadequate pressure was generated because of triangular and square pin profiles that may have given high resistance to deformation and less axial pressure which ultimately caused in lack of surface fill and big voids in key hole [2, 3]. In addition to this, there were variations in shoulder surface area that may have resulted in inappropriate heat input and caused cold conditions. These conditions may have formed the defects such as lack of surface fill and voids [5]. On the other hand, there were no surface defects observed on the weld of hexagonal tool pin profile.

Cross sectional view of second set of experiments are shown in Fig: 7. Defects such as voids, pores and cracks were reported in all the welds. Big sized voids were observed in large amount at the weld made by triangular pin profile (see Fig: 7 a). These voids were caused because of presence of large Cu particles in the stir zone. The cracks were also reported in some area because of large fragments of Cu particles. The large Cu particles were detached from Cu base material due to three sharp edges [3]. Similarly, fragmental defects such as micro cracks and voids were reported in the welds made by square and hexagonal tool pin profiles as shown in Fig: 7 (b and c). These defects were generated due to same reason. Here, the Cu fragments were responsible for these defects, but the defects were less compared to the weld of triangular pin profile [2, 3]. Minimum defects were reported in the weld of hexagonal pin profile. As the number of edges increases, the scratching of Cu particles becomes smaller and lesser that consequently reduces the fragmental defects [3]. Moreover, variations in the tool shoulder surface also vary the heat input conditions that may have generated these defects.



(a) (b) (c)

Fig: 6 visual observation of welds made by different pin profiles having constant static volume such as (a) triangular, (b) square and (c) hexagonal; defects: (a) lack of surface fill and void in key hole and (b) surface pore and voids in key hole

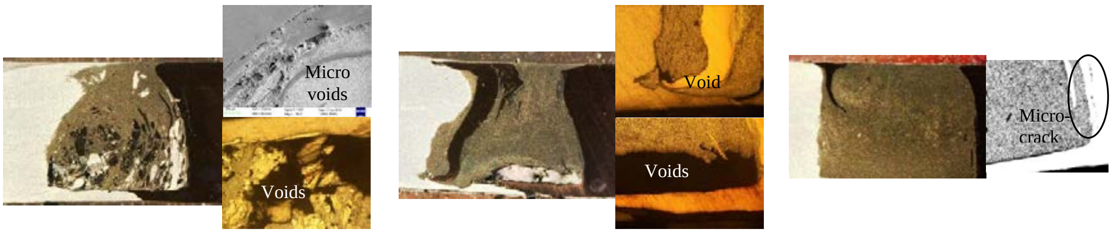


(a) (b) (c)

Fig: 7 cross sectional view of welds made by tool having pin profiles designed based on constant static volume: (a) triangular, (b) square and (c) hexagonal

In the third set of experiments, the tool pins were designed based on its dynamic volume with reference to cylindrical tool pin profile having PD: 8 mm. The shoulder surface was remain constant for all three pin design due to its constant dynamic volume. The visual examination of third set of experiments are shown in Fig: 8. Lack of surface fill and void in key-hole was again reported in the weld of triangular pin profile while there were no defects found in the welds of pin profiles such as square and hexagonal pin profiles. It can be interpreted that same area of shoulder surface have reduced the surface defects and key-hole defects with great extent. Enough axial pressure may have produced by these shoulder surfaces that have reduced the defects [3]. Cross sectional view of welds made by polygonal pin profiles having constant dynamic volume of pin are shown in Fig: 9. Voids and micro cracks were reported as major defects in all the welds [3, 18, 19]. Aforementioned, weld made by triangular pin profile consisted of large amount of defects in the weld while hexagonal pin profile was having minimum defects (refer Fig: 9 a). Hair sized cracks were reported in the weld of hexagonal pin profile (see Fig: 9 c). As discussed earlier that, the large Cu particles detached from Cu base material were responsible for defects. Minimum polygonal edges have detached large Cu particles and resulted in defects while increase in polygonal edges reduces the defects.

Fig: 8 visual observation of welds made by different pin profiles having constant dynamic volume such as (a) triangular, (b) square and (c) hexagonal; defects: (a) lack of surface fill and void in key hole



(a) (b) (c)

Fig: 9 cross sectional view of welds made by tool having pin profiles designed based on constant dynamic volume : (a) triangular, (b) square and (c) hexagonal

4. Conclusions

Experimental study for dissimilar copper-aluminum FSW was carryout to elucidate the effect of different tool pin design on defects formation. Following conclusions can be made from present investigation.

- The copper particles detached from base material were large and irregular in case of polygonal pin designs.
- Maximum irregular and large copper particles were reported in welds made by triangular pin profiles. Additionally, polygonal pin profiles were caused the defects such as voids, cracks and fragmental defects irrespective of its static and dynamic constant areas.
- The defects were decreased as the polygonal edges increases.
- Defect free macro joint was reported for cylindrical tool pin profile.

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