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Numerical modeling of friction stir welding using the tools with polygonal pins

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Abstract

Friction stir welding using the tools with polygonal pins is often found to improve the mechanical strength of weld joint in comparison to the tools with circular pins. However, the impacts of pin profile on the peak temperature, tool torque and traverse force, and the resultant mechanical stresses experienced by the tool have been rarely reported in a systematic manner. An estimation of the rate of heat generation for the tools with polygonal pins is challenging due to their non-axisymmetric cross-section about the tool axis. A novel methodology is presented to analytically estimate the rate of heat generation for the tools with polygonal pins. A three-dimensional heat transfer analysis of friction stir welding is carried out using finite element method. The computed temperature field from the heat transfer model is used to estimate the torque, traverse force and the mechanical stresses experienced by regular triangular, square, pentagon and hexagon pins following the principles of solid mechanics. The computed results show that the peak temperature experienced by the tool pin increases with the number of pin sides. However, the resultant maximum shear stress experienced by the pin reduces from the triangular to hexagonal pins.

Keywords: Friction stir welding; Polygonal tool pin; Aluminum alloy; Numerical model; Tool durability

1. Introduction

The influences of tool shoulder and pin geometry on the microstructure and the tensile properties of the weld joints in friction stir welding (FSW) have been studied extensively [1–5]. The tools with non-circular pin profiles were recently used for FSW with an aim to enhance the flow of the plasticized material and the resulting joint quality [6,7]. The pins with the regular polygonal shapes, such as triangular [8–12], square [13–20], and hexagon [21], and the complex profiles, such as triangular with a convex periphery, circular with three flats, three flutes and four flutes, which are referred to as trivex, triflat, triflute and quadflute, respectively, are considered [6,7,10]. The pin profiles with the regular polygon shape are preferred in comparison to the complex non-circular shapes because of the ease of manufacturing of the former ones. The relative performance and the longevity of the tools with circular and non-circular pins during FSW were also reported recently [22]. Although many of these studies have indicated the improved performance of the tools with the polygonal pins in comparison to the circular pins, the influences of the polygonal pin cross-section on the peak temperature, and tool torque and forces have been rarely studied using a quantitative numerical model.

Colegrove et al. reported that the Trivex pin profile could prevent material entrapment and reduce shearing force on the advancing side of the pin, resulting in lesser pin traverse force compared to the Triflute pin profile [6]. In subsequent studies, Colegrove, et al. found the Triflat pin to produce the best welds followed by the Triflute and Trivex profiles although the

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Triflat pin increased the total torque [7] and [8]. Fujii et al. reported greater joint strength in FSW of AA5083 using the tool pins with triangular cross-section at a rotational speed of 1500 rpm and at varying weld pitch compared to a circular pin profile[12]. The tool pins with square cross-section provided the best mechanical properties of weld joint for a range of welding conditions in FSW of SiC reinforced AA1050 [13], AA6061 [14] and [15], Al-10 wt.% TiB_2 MMC [16], AA2219 [19] and [20], and in dissimilar materials of AA5083 and AA6351 [18] compared to the other pin profiles. Amongst the pins with several polygonal cross-sections, a typical hexagonal pin profile provided superior tensile properties of weld joint in FSW of AA2014 although the joint properties obtained with the square, pentagon and hexagonal pins did not show any significant variation [21]. Most of these studies on FSW with polygonal pin profiles concentrated on the testing and characterization of the final weld joints.

The present work depicts the development of a three-dimensional heat transfer analysis of FSW process following a novel methodology to analytically estimate the rate of heat generation for tools with polygonal pins shapes. The area of contact between the flat faces of polygonal pins and the plasticized material is estimated based on the principles of orthogonal machining [22]. A three-dimensional steady state heat transfer model of FSW process is developed using finite element method to compute the temperature fields in the workpiece and the tool pin. The computed temperature distribution of the workpiece material surrounding the tool is used to analytically estimate the torque and traverse force experienced by the tool. The computed values of thermal cycle, torque and traverse force are validated with the corresponding experimentally measured results for FSW of AA2014-T6. The estimated values of the pin traverse force are used to compute the stresses on polygonal pin profiles based on the principles of solid mechanics.

2. Experimental study

300 mm (length) × 100 mm (width) × 5 mm (thickness) aluminum alloy (AA2014-T6) plates are welded by friction stir welding in square butt joint configuration using EN40 tools with constant shoulder diameter of 12 mm and pin length of 4.7 mm. The rotational and linear speeds, the axial pressure and the tool tilt angle are kept constant for all the welds, which are 1000 rpm, 7.73 mm/s, 90 MPa and 2°, respectively. Four different tool pins with triangular, square, pentagon and hexagon profiles are used. Since the pins are tapered along the length, the side lengths of each pin profile at the root and at the tip are different (Table 1). The circumcircle diameters of all the polygonal pins are 6 mm and 3.6 mm at the root and at the tip, respectively. Table 2 depicts the compositions of the workpiece and the tool materials [23] and [24]. Table 3 provides the thermophysical properties of the workpiece material [25]. The density, specific heat and thermal conductivity of the tool material are considered as 7850 kg/m^3, 485.34 J/(kg·K) and 34.73 W/(m·K), respectively [25]. The transient thermal cycles are measured using K-type thermocouples during the actual FSW experiments with a transverse distance of 4 mm from the original weld joint interface and at a depth of 2 mm from the top surface. The torque and the traverse force are also measured during the actual FSW process.

Table 1
Tool pin geometry.

Regular polygon pin profile	Pin side length/mm	
	Root	Tip
Triangular	5.19	3.11
Square	4.24	2.54
Pentagon	3.52	2.11
Hexagon	3.0	1.8

3. Theoretical formulation

A steady state three-dimensional heat conduction analysis of the FSW process is carried out with the governing differential equation

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{Q}=\rho C U_1\frac{\partial T}{\partial x} \tag{1}$$

where ρ, k, C and U_1 refer to the density, thermal conductivity, specific heat, and the constant welding speed, respectively; and T is the temperature variable. The term $\dot{Q}$ accounts for the rate of internal heat generation per unit volume. The rate of the frictional heat generation per unit area (q_S) at the tool–workpiece interface is applied as a surface flux and estimated as [26,27]

$$q_S=\eta_h\times\left[\eta_m(1-\delta)\tau_y+\delta\mu_f P_N\right](\omega r-U_1\sin\theta) \tag{2}$$

where η_h is the fraction of heat transferred to workpiece; η_m depicts the fraction of mechanical work due to sticking friction converted to heat; P_N is the axial pressure; τ_y is the temperature-dependent shear yield stress of deformed material; r is the radial distance from tool axis; θ is the orientation of the point from the welding direction; ω is the angular speed; and, δ and μ_f refer to the local variations in fractional sliding and the coefficient of friction, respectively. A symmetric analysis is undertaken considering the plane of symmetry along the original weld joint interface. The rate of heat generation along the pin – workpiece interface is applied as a volumetric heat input by multiplying q_S by A_i/V_i where A_i and V_i refer respectively to the surface area and volume of the i-th discrete element adjacent to the tool pin surface [26,27]. A temperature-dependent convective heat transfer coefficient as $h_b\times(T-T_0)^{0.25}$ is applied along the bottom surface, where

Table 2
Composition of workpiece [23] and tool material [24].

AA2014-T6 (Workpiece)	Element	Al	Cu	Si	Mn	Mg
	wt./%	90.4–95.0	3.9–5.0	0.5–1.2	0.4–1.2	0.2–0.8
EN40 (Tool)	Element	C	Mn	Si	Cr	Mo
	wt./%	0.3–0.5	0.4–0.8	0.1–0.35	2.5–3.5	0.7–1.2