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Friction stir channeling: Characterization of the channels

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ABSTRACT

Commercially available compact heat exchangers are currently fabricated in several steps by joining multiple tubes, or by independently fabricating and joining fluid channels. Friction stir channeling (FSC) is a simple and innovative technique of manufacturing heat exchangers in a single step by creating continuous, integral channels in a monolithic plate in a single pass. FSC relies on the frictional heat generated between the tool material and the metal workpiece to soften and deform the material to facilitate the creation of a continuous channel. The channel shape, size, and integrity depend on the processing parameters and the tool design. In this paper the structural characteristics and the relationship between the channel features and the processing parameters are discussed. FSC is being developed as a technique for manufacturing heat exchangers. The channel is characterized by roughness features on the inside, which can be analyzed using optical microscopy techniques.

1. Introduction

Friction stir welding (FSW) and friction stir processing (FSP) are emerging as very effective solid-state joining/processing techniques. FSW was invented at The Welding Institute (TWI) of UK in 1991 as a solid-state joining technique, and it was initially applied to aluminum alloys (Thomas et al., 1991). In this process, a non-consumable rotating tool with a pin and shoulder is inserted into the abutting edges of the sheets to be joined and traversed along the line of joint. Frictional and deformational heat is generated due to tool–work material interaction. The combination of the tool rotation and tool traverse moves the material from the front of the pin to the back of the pin. During this process, the material undergoes intense plastic deformation at an elevated temperature and results in a fine-grained microstructure in the stirred region (called a "nugget") (Reynolds, 2007). FSP is an adaptation of FSW and is used as a generic tool for microstructural modification of materials based on the principles of FSW. Some of the unique features of FSW such as the low amount of heat generated, extensive plastic deformation and controlled flow of material is being used to develop new material modification and manufacturing processes (Mishra and Ma, 2005).

During FSW, a defect referred to as a "wormhole" is generated if the processing parameters and tool shoulder contact are not proper. FSC is based on converting this defect formation process into a manufacturing technique for heat exchanger applications. Mishra (2005) has shown that a continuous hole in a single plate can be achieved by selecting the right processing conditions and reversing the material flow. The main aspects of FSC are as follows:

(a) the profiled tool is rotated such that the material flow is upwards towards the tool shoulder,
(b) an initial clearance is provided between the shoulder and the workpiece, where the material from the base of the pin is deposited and

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(c) this distance between the tool shoulder and the workpiece can be adjusted to control the shape, size, and integrity of the channel.

The presence of the gap between the shoulder and the workpiece is a major difference between the FSC and the normal FSW or FSP practices where the back of the shoulder touches the workpiece to generate the forging action required to produce defect-free welding or processing. During channeling, an upward force is generated by rotating a right-hand threaded tool along clockwise direction (or a left-hand threaded tool along counter clockwise direction). A channel is formed because of the separation of the plasticized material around the pin from the plasticized material at the base of the pin. This separated material is moved upwards by the rotation of the pin and the orientation of the threads, and it is deposited on the top of the nugget underneath the shoulder surface. The shape and size of the channel can be controlled by varying the following parameters: the clearance between the shoulder and the work material, the tool rotation speed, the tool traverse rate and the tool design.

The generation of a continuous channel by FSC has the potential to open a wide range of applications in heat exchanger industry. Heat exchangers are devices that are used to transfer thermal energy between two or more fluids, or between a solid surface and a fluid, at different temperatures and in thermal contact (Shah and Sekulic, 2003). Typical applications of heat exchangers involve heating or cooling of a fluid stream and evaporation or condensation of fluid streams, with an objective to reject or recover heat. Heat exchangers are usually classified on the basis of the transfer process, as either direct contact type or indirect contact type. The heat exchangers are also classified on the basis of the number of process fluids, or on the basis of the construction or flow arrangements or the heat transfer mechanisms. Another basis for classification of the heat exchangers is on the basis of surface compactness. The main objectives of compact heat exchangers are to maximize the efficiency of a heat exchanger and also to reduce the size of the heat exchanger for a given duty. Compact heat exchangers are generally used in industry, especially in gas-to-gas or liquid-to-gas heat exchangers. For example, vehicular heat exchangers, condensers and evaporators in air-condition and refrigeration industry, aircraft oil-coolers, automotive radiators, and intercoolers or compressors.

Compact heat exchangers are generally used in gas flow applications. These heat exchangers have a surface area density higher than 700 m^2/m^3; i.e., they have a higher heat transfer surface area per unit volume. The principles of heat exchanger design have been applied to micro-scale devices, resulting in basic designs comparable to those known from macro-scale devices, such as cross-flow or counter-flow heat exchangers, but providing much smaller characteristic dimensions (Brandner et al., 2006). Wadekar (2005) has examined industrial heat exchangers where mini- and micro-scale heat transfer are of significance. The most important of these characteristic dimensions are the distance between heat sink and heat source, and the hydraulic diameter D_h. The hydraulic diameter is a term commonly used when handling flow in non-circular tubes and channels and is defined as the ratio of four times the area of the cross-section to the wetted perimeter of the channel. On the basis of the hydraulic diameter, compact heat exchangers have been classified into micro-heat exchangers (D_h = 1–100 μm), meso-heat exchangers (D_h = 0.0001–1 mm), compact heat exchangers (D_h = 1–6 mm) and conventional heat exchangers (D_h > 6 mm) (Mehendale et al., 2000). A different system of classification on the basis of the minimum channel dimension (D) has been proposed by Kandlikar and Grande (2004) as shown in Table 1. The channels obtained using FSC have a D of 0.2–2 mm and therefore fall in the minichannels category on the basis of Kandlikar's classification. Also the friction stir channels have irregular shapes and fluid flow through irregular geometries has been dealt extensively in the literature. Wu and Cheng (2003) have studied the flow characteristics inside trapezoidal microchannels with different aspect ratios. Li et al. (2006) have performed numerical simulations of the flow and heat transfer of fluids inside microchannels with non-circular cross-sections (trapezoidal and triangular). Hrnjak and Tu (2007) have summarized the list of experimental studies that have been done in regular and irregular shaped microchannels and studied the pressure drop inside rectangular microchannels at different flow rates and for different test fluids.

Table 1 – Channel classification (Kandlikar and Grande, 2004).

Conventional channels	$D > 3$ mm
Minichannels	$3\,\text{mm} \geq D > 200\,\mu\text{m}$
Microchannels	$200\,\mu\text{m} \geq D > 10\,\mu\text{m}$
Transitional channels	$10\,\mu\text{m} \geq D > 0.1\,\mu\text{m}$
Transitional microchannels	$10\,\mu\text{m} \geq D > 1\,\mu\text{m}$
Transitional nano-channels	$1\,\mu\text{m} \geq D > 0.1\,\mu\text{m}$
Molecular nano-channels	$0.1\,\mu\text{m} > D$

Presently, compact heat exchangers are manufactured using metal removal processes like micromachining and are later assembled and joined using metal joining techniques. Tsopanos et al. (2005) have used selective laser melting, a layer-based solid freeform fabrication technique to create micro cross-flow heat exchangers from stainless steel powder. If used to manufacture heat exchangers, FSC offers the benefit of a single step channel fabrication process. The objectives of this paper are to discuss the channel characteristics for different process parameters and also to prove the stability of the channel along curved profiles, seen commonly in heat exchangers.

2. Experimental procedure

Commercial 6061 Al alloy was selected for the study. Three different tools with cylindrical pins and left-handed threads were used in this investigation. All the tools had a shoulder diameter of 16 mm, pin diameter of 5 mm, and pin length of 4 mm. Tool 1 had a thread pitch of 1.25 mm, a thread angle of 60° and a depth of cut of 0.4 mm. The equivalent numbers for tool 2 were 1.25 mm, 60° and 1 mm; and for tool 3 were 1.25 mm, 75° and 1.6 mm, respectively. The tools were rotated in the counter clockwise direction as seen from the top of the workpiece. The intent of these runs was to obtain channels with no visible surface defects and of maximum size. The process parameters (the tool rotation rate, traverse speed, and the