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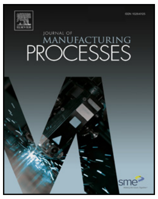

Fabrication of cooling channels employing worm voids caused by friction stir based process: Considering cooling and fluid parameters

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ABSTRACT

The developments in compact high power mechanical and electrical devices naturally require heat removal systems that are equally small. Miniaturized heat exchangers (MHE) are manufactured either by joining multiple tubes or by connecting independent fluid channels fabricated in several steps. Friction stir channeling (FSC), is an innovative cost-effective technology that can be practically employed to reduce the fabrication process of connected channels into a single step. For this reason, the effects of manufacturing parameters of FSC on the main design factors of MHE should be clearly known. In the present study, novel tools are designed based on a comprehensive understating of complex material flow in friction stir based process (FSBP). These tools are proposed both to facilitate material separation and to enhance the amount of material removed from the channel holes. The FSC designed tools are experimentally employed in both laminar and turbulent flows to investigate the effects of tool geometry on the main performance parameters of cooling ducts. Flow resistance along with convection and conduction thermal resistances are introduced in this study to explore the produced channels. Evaluation of each tool by considering the geometrical, thermal, and flow parameters clearly indicates that the bi-directional threaded diamond-shape FSC tool is a viable tool that can pave the way for developing efficient thermal and flow designs in MHE systems.

Introduction

Friction Stir Based Process (FSBP), is a solid-state technique that was invented in 1991. In this process, a specially designed rotating tool is first inserted into a metallic sheet and is further moved with a longitudinal speed. Such a tool produces frictional and plastic deformation heating without reaching the metal melting point. Furthermore, as the tool moves, the material is forced to flow around the tool in a complex flow pattern [1]. Unsuitable metal flow pattern leads to the formation of wormhole volumetric voids which is considered to be a serious undesirable defect that should be eliminated. This lack can be resulted from inadequate heat input, followed by poor plastic deformation [2] as well as improper direction of material flow in different zones.

FSBP principles were first introduced through friction stir welding (FSW). Then, they were developed in the field of surface engineering technology under the title of friction stir processing (FSP) [3,4]. Recently, these principles have been developed by the introduction of friction stir channeling (FSC) as a method of small cooling channel production. FSC, first introduced by Mishra [5] as an adoption of FSBP, is based on the conversion of the wormhole volumetric voids into desired channels. Mishra's patents provide confirmatory evidence on the importance of tool pin thread direction and also the clearance between the faying surfaces of tool shoulder and the workpiece. Contrary to the classic FSBP process, the combination of rotation and thread directions must guarantee the upward flow of material and the stated clearance should allow the evacuated channel material to flow out of the part. The seamless non-linear channels formed by FSC provide numerous applications including the formation of appropriate flow passages for working fluid through Miniaturized Heat Exchangers (MHE). If the geometrical and internal surface characteristics are in accordance with the cooling and fluid design factors, then such a technology will significantly increase the efficiency of MHE systems.

To clarify the revolutionary influence of FSC as a novel method for manufacturing MHE, other available techniques are succinctly reviewed in the upcoming paragraphs:

MHE applications refer to a wide variety of technologies, including automotive, aerospace, bioengineering, microelectronics, and thermal control of film deposition. These applications can be categorized into three main types: (I) biological applications, (II) chemical applications,

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and (III) applications pertaining to electronics and mechanical engineering [6]. Various methods have been proposed for the production of cooling channels in MHE applications. These methods can be divided into traditional and modern techniques. The traditional methods include micro deformation, micro sawing, and micro milling, whereas the modern methods include chemical etching, micro-electro-mechanical systems (MEMS), laser micromachining, electric discharge machining, and micro molding [7]. While conventional manufacturing technologies have been considered as a hard-hitting task, modern techniques have paved the way for much more easier, cheaper, and efficient production of MHE. In addition to the above-mentioned classification, these manufacturing processes can also be categorized into subtractive, additive, mass containing, and joining ones [8].

In general, each of the aforementioned methods has its own merits and demerits that depend on the material in which the channels can be formed as well as the limitations imposed by time, size, and cost constraints. MEMS, as an additive process, has been widely used due to its low manufacturing uncertainty. Laser micromachining, as a subtractive method, has been very popular due to the high precision and performance in forming the shape of the cross-sectional area of the channel. Among the joining methods, brazing has been so popular due to the low cost and accommodation to complex structures and has been greatly improved in recent years [9–11]. Despite the progresses made in joining methods, several-step fabrication of small cooling channels still needs some evolutions. A brief comparison between some of the most common fabrication methods has been presented in Table 1. While the developments regarding these fabrication methods are undeniable, numerous serious challenges are still encountered in the fabrication of desired-path channels, such as performing single-step cost effective manufacturing process and efficient production of internal channel. Efficient production of internal channels is crucial in cooling systems where the working fluid cannot be in direct contact with the equipment, i.e. in systems containing an electric current.

By overcoming the noted challenges, FSC takes advantage of FSBP unique properties of fine grain size in the stirred zone, low distortion, excellent mechanical properties, and suitability for automation. It is worth mentioning that, another factor that distinguishes FSC from other methods is the possibility of channel formation without the need to access the cross-section of the part and also without affecting the functionality of the part.

Underlying the imperative role of FSC in probable future production of heat exchangers, Ferraz [12] performed different strengths, weaknesses, opportunities, and threats (SWOT) analysis by comparing FSC with three alternative technologies of EDM, milling, and drilling. It was shown that FSC obtains the compromise between the pros and cons of alternative technologies and has the potential to cover the industry with a rapid growing rate. Furthermore, his work demonstrated that FSC process can be successfully employed in the mold industry, including both injection and open molding techniques.

In recent years, suggestion of various versions of FSC method has caused a remarkable progress in the industrialization of FSC. Vilaca et al. [13] claimed that the necessity for existence of clearance between the faying surfaces of the tool shoulder and the workpiece can be eliminated by accurate assortment of FSC functional parameters in parallel with advanced design of FSC tools. In a following investigation, it was also proved that the shape, size, and integrity of channels are well-disciplined in terms of process parameters and can correspondingly be optimized regarding the encountered application field [14]. In a more recent survey, Rashidi et al. [15,16] introduced modified FSC as an alternative technique for the production of channels with more regular shapes. In this method, a non-threaded tool pin with tilt angle was applied; therefore, a new material model was proposed for this specified version for which its accuracy was also explored.

Adopting the maturity of FSC process as a competitive method, several researchers have merely focused on exploring FSC variables and functional parameters to reach more specific process design. In this regard, Balasubramanian et al. explored the functionality of the produced MHE channels by experimentally recording pressure drop and measuring the inlet and outlet temperature differences as the main output parameters [17]. Also, they analyzed the net force plot in the stirred zone as the main controlling variable [18]. In perpetuation of the previous study as well as the achievements made there, they also tried to predict the occurrence of channels through an energy-based model as a function of tool rotation rate, traverse speed, and plunge depth [19].

Despite the mentioned investigations that attempted to cover different aspects of FSC, there is no systematic study conducted to scrutinize the effect of FSC parameters, including tool shape on the main analytical cooling and flow factors. These fluid factors can be employed during the designing process of a MHE and they can provide vital understanding for designers of MHEs.

The current study aims to introduce a FSC tool shape that leads to more efficient analytical fluid and cooling characteristics and to study the effect of choosing FSC tool on the main design factors of MHEs. To address this, the effect of tool shape on the physical characteristics of the formed channels, including internal surface roughness, hydraulic diameter, effective cooling area, and the distance of the channel from the surface are extracted. Subsequently, the analytical cooling and fluid factors for the channel fabricated by each tool, including fluid resistance and heat transfer are studied for both turbulent and laminar flow. Finally, by considering the mentioned analytical factors, a unique score is attributed to each tool to facilitate choosing a FSC tool that provides the best cooling and fluid characteristics for the fabricated channels.

Table 1
Comparison of some small-scale channels manufacturing methods [6].

	Micro Deformation	**Micro Machining**	**MEMS**	**Laser Micro Machining**
Geometries	Rectangular	Rectangular	Rectangular Circular Triangular Trapezoidal	Unlimited
Materials	Metal and Non-Metal	Metal & Silicon	Metal, Silicon & Glass	Metal & Glass
Channel Range	250 channels/inch	0.1-10 mm	Nanometer scale to millimeter scale	Nanometer scale to millimeter scale
Advantages	Low cost, fast	High or low aspect ratio, inexpensive, fast	Low manufacturing uncertainty	Low manufacturing uncertainty
Disadvantages	Post treatment	Complex design is impossible	Slow process	Too expensive