CIRP Annals - Manufacturing Technology 65 (2016) 289–292

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Design and optimization of stamping process of ultra-thin stainless sheet into bidirectionally corrugated shape for finless high-efficiency heat exchanger

Jun Yanagimoto (1)[a,*], Yasuhito Wake[b], Pascal Zeise[c], Hung Mao[d], Naoki Shikazono[a]

[a] *Institute of Industrial Science, the University of Tokyo, Komaba 4-6-1, Meguro, Tokyo 153-8505, Japan*
[b] *Waki Factory Inc., Higashi-Sayamagaoka 6-760, Tokorozawa, Saitama 359-1106, Japan*
[c] *Technische Universität Darmstadt, Otto-Berndt-Straße 2, 64287 Darmstadt, Germany*
[d] *Graduate School of Engineering, the University of Tokyo, Komaba 4-6-1, Meguro, Tokyo 153-8505, Japan*

ARTICLE INFO

Keywords:
Stamping
Sheet metal
Finless heat exchanger
Fracture
Finite element method

ABSTRACT

The stamping of an ultra-thin stainless steel sheet into a wave shape for a finless heat exchanger was investigated. As an alternative to fins made by the extrusion or drawing, a bidirectionally corrugated shape is advantageous because of its higher efficiency in heat exchange with smaller resistance to an ambient air flow. A greater wave height is advantageous, but is suppressed by fracture during stamping. A new stamping method was developed to realize a high-efficiency heat exchanger using an ultra-thin stainless steel sheet with an optimized corrugated shape in terms of the plan-view pattern and cross-sectional profile.

1. Introduction

Environmental impact has attracted the concern of society, and its reduction in manufacturing processes is being discussed by the academic community as in CIRP keynote 2012 [1]. The utilization of fossil energy has been an essential platform to support modern industrialized society. As a representative example, a gas turbine generator requires the recovery of exhaust heat to ensure thermal efficiency. A heat exchanger is an indispensable component of thermal engines, and achieving higher thermal efficiency to reduce environmental impact requires a heat exchanger with a higher thermal exchange rate or efficiency.

A heat exchanger is a typical product made of metals as it requires high thermal conductivity and corrosion resistance. In the past, heat exchangers were made of metallic parts such as fins or tubes, which were shaped into the desired geometry by casting, or by metal forming such as extrusion and drawing from a bulk billet. Nowadays, conventional fin-shaped exchangers are widely used such as in aluminum radiators in vehicles. Attempts to reduce environmental impact have led to two paradigm shifts in heat exchangers. The first shift involves the weight and volume reduction. In a conventional heat exchanger, which is illustrated in Fig. 1(a), heat is exchanged between metal fins and flowing ambient air. Here, the fluid temperature is higher, thus, this heat exchanger is used as the radiator to cool a fluid. The area of the fins should be sufficiently large, but the ambient air should flow between the fins with low resistance. Thus, the fins cannot be too closely stacked in a conventional fin-shaped heat exchanger, which limits not only the rate of heat exchange [2], but also the reduction of volume and weight of heat exchanger. The second shift is a marked increase in the demand for heat exchangers in the exhaust heat recovery cycle, which have become more common in gas turbines in combined cycles, construction machines, sintering furnaces and heating furnaces for industrial use, and fuel cells. This trend has promoted the use of stainless steel with excellent corrosion resistance; however, forming thin stainless fins or tube parts by extrusion and drawing is difficult or almost impossible. Note that, in a heat exchanger in an exhaust heat recovery cycle, the temperature of the ambient air (gas) is higher than that of the fluid (coolant), and the exhaust gas is very corrosive.

To respond to the above two paradigm shifts for heat exchangers by realizing high efficiency and high corrosion resistance, a heat exchanger based on a completely new concept is proposed [3]: the stainless finless heat exchanger schematically illustrated in Fig. 1(b). Here, stamping is used to form the parts, and a pair of stainless sheets (stamped front sheet and stamped rear sheet) is used to form a flat tube with a liquid flow channel after brazing. To promote heat transfer between the liquid in flat tube and the ambient air flow, a macroscopic surface texture, such as a bidirectionally corrugated shape (hereinafter it is called as an oblique wave shape) [3], is stamped on the ultra-thin stainless sheet with a thickness of 0.3 mm. Then flat tubes are stacked to construct a heat exchanger with a liquid flow channel inside each tube. The efficiency of such a finless exchanger is higher than that of a conventional fin-shaped heat exchanger in terms of heat exchange rate at the same resistance to the ambient air flow. The

---

[*] Corresponding author.
E-mail address: yan@iis.u-tokyo.ac.jp (J. Yanagimoto).

http://dx.doi.org/10.1016/j.cirp.2016.04.127

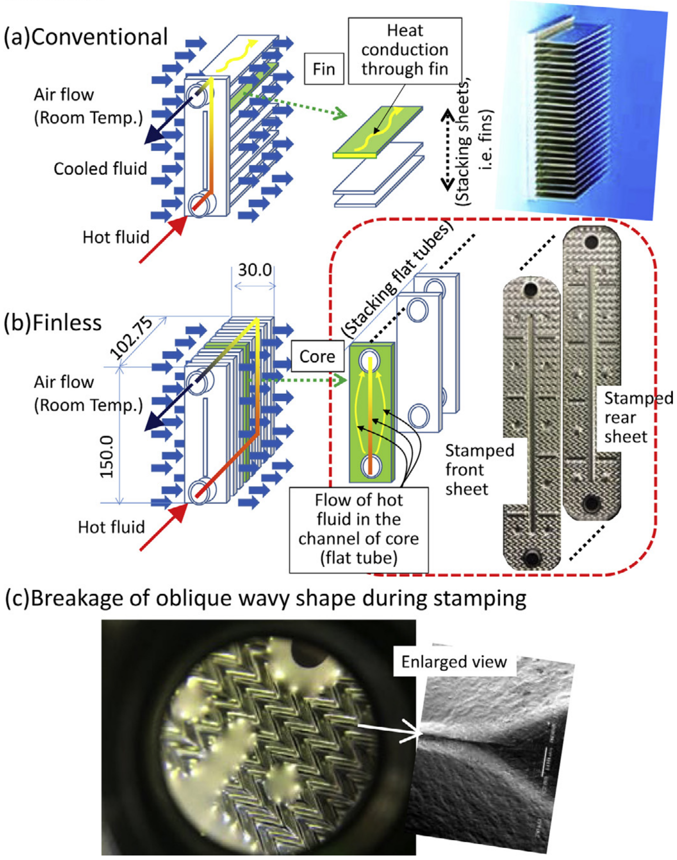

Fig. 1. Comparison between conventional fin-shaped heat exchanger and finless heat exchanger with its macroscopic surface texture.

higher the wave is, the higher the heat exchange rate will be. Thus, the design of the stamping process and the geometries of dies to increase the oblique wave height is the primary concern in the research and development of our finless heat exchanger. Stamping of the ultra-thin stainless sheets of 0.3 mm thickness, or 0.1 mm thickness in some cases, is required to increase the efficiency and reduce the material cost of heat exchangers. However, stamping a wave shape on ultra-thin stainless steel is difficult because of the high plastic deformation locally imposed on the sheet. A higher amplitude of the wave shape on the stainless sheet is necessary to attain the desired efficiency, but this will result in the breakage of a thin sheet, as shown in Fig. 1(c), when the plastic deformation exceeds the limit of elongation of stainless steel.

Stamping of ultra-thin sheet with the thickness of 0.3 mm or less has not been investigated well in the past, because the main application of sheet forming is the parts for vehicle bodies with the thickness around 1 mm or more [4,5]. Ultra-thin sheets with the thickness less than 0.3 mm were applied to MEMS devices [6,7], micro drawing [8], and the metallic bipolar plate for polymer electrolyte membrane fuel cells [9]. To produce a finless heat exchanger with excellent efficiency, the stamping of a higher wave shape to the ultra-thin stainless sheet is crucial because they affect the specifications of the heat exchanger.

In this study, the design and optimization of the cross-sectional profile and plan-view pattern to realize the sound stamping of ultra-thin sheets into oblique wave shapes with large wave height are investigated. This investigation deals with the precise shaping technology of sheets by stamping to generate the macroscopic texture to promote heat transfer; this is not only the technology of shaping, but is a typical example beyond shaping as summarized in recent CIRP keynote [10], because sound shaping adds value to a stamped sheet such as excellent heat exchange efficiency.

2. Target heat exchanger and experiment using an original oblique shape

2.1. Target heat exchanger

The heat exchanger in the exhaust heat recovery cycle of a fuel cell for domestic use is taken as an example. In particular, solid oxide fuel cells (SOFCs) are expected to become common owing to their excellent efficiency of 60% or more. A schematic of an SOFC and its exhaust heat recovery cycle is illustrated in Fig. 2.

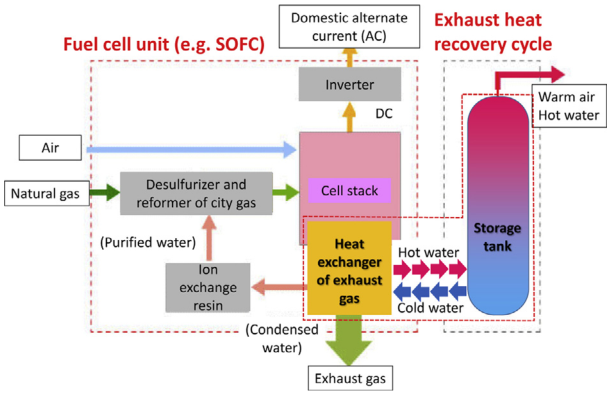

Fig. 2. A schematic of an SOFC and its exhaust heat recovery cycle.

2.2. Experiment on maximum height of original oblique wave

Two directions in which the geometry of an oblique wave shape was evaluated in this study are shown in Fig. 3. In the cross-sectional direction, the stamped geometry is periodic. From the top of the stamped sheet, an oblique wave shape to enhance heat transfer to the flowing ambient air can be observed. The flowing direction of the ambient air is shown in Fig. 3. Table 1 summarizes the geometrical parameters of dies. Note that this table includes parameters of newly designed oblique wave shape which will be discussed in next chapter, as well as those of a finless heat exchanger with original shape which will be discussed in this section. Definition to geometrical parameters is shown in Fig. 4. Parameters affecting the plastic deformation during forming are: (1) Periodic wavelength L, (2) Oblique angle θ, (3) Wave

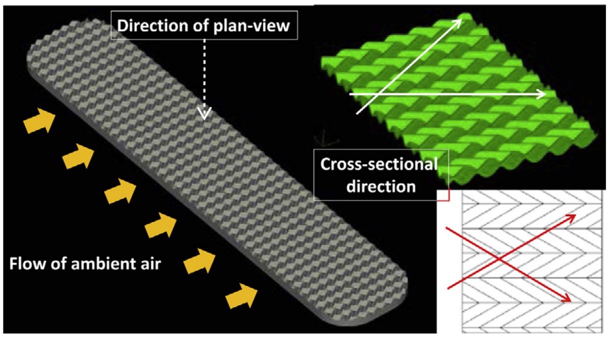

Fig. 3. Definition of cross-section and plan-view patterns.

Table 1
Plan-view patterns and cross-sectional profile of die.

	Original shape	Newly-designed shape in chapter 3
Wave distance D (mm)	1.80	1.80
Oblique angle θ (degree)	30.0	39.5
Periodic wavelength L (mm)	1.56	1.98
Radius of flection (mm)	None (≃0)	0.55
Cross-sectional shape of a wave	Sine curve	Round + straight
Radius of wave (at top position) (mm)	$(2\pi/L)^{-2} \simeq 0.063$	0.50