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Letters

Manufacturing of surface features from extrusion forging and extrusion rolling of sheet metals

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ABSTRACT

Engineered surfaces are commonly designed to achieve certain desirable functionalities. Manufacturing of engineered surfaces often requires innovative techniques. In this paper, a sheet metal surface with pin fin features is proposed for potential thermal or fluid flow management applications. Experiments and numerical simulations were carried out to demonstrate that extrusion-forging process can be used to create such micro scale surface features. Preliminary results from simulations also show that it is feasible to use extrusion-rolling process to manufacture pin fin features to increase productivity and reduce cost. The work suggests that extrusion-rolling technique has good potential for large scale manufacturing of various innovative surfaces features.

1. Introduction

Engineered surfaces are commonly designed to deliver certain desired functionalities. For example, coatings are applied to part surfaces for decoration, corrosion resistance, or thermal barrier purposes. Surface textures are produced to control friction and wear, improve seal, or increase fatigue life. In a different scale, surface features such the dimples on a golf ball and pin fins of a heat sink are created to enhance performance. The dimples are designed to reduce drag and increase lift so a golf ball can travel farther. Pin fins are surface protrusions that can facilitate heat dissipation for electronics cooling.

When incorporating low profile pins/bosses on sheet metal for folded fin heat sink, as depicted in Fig. 1 [1,2], the heat removal performance could be further enhanced. As such, manufacturing of protruded surface features, such as a pin fin array, on sheet metal is of interest in the present study.

Creating protruded surface features on sheet metal, however, presents interesting technical challenges. Extrusion-forging is a bulk metal forming process that combines extrusion and forging into one single operation. The workpiece is compressed between two flat parallel dies, with one of the dies containing a hole [3]. Both analytical and numerical models were developed to calculate the force/pressure [4–7]. The effects of friction and draft angle of the hole on forming force have also been studied [3,8,9]. While the extrusion-forging process has been widely investigated, the workpiece is a billet instead of a metal sheet. More relevant work in bulk forming of sheet metal can be found in a review paper by Merklein et al. [10]. In sheet metal extrusion, the extrusion punch penetrates one surface of the sheet metal to cause the material to extrude and flow toward the outlet of the die in the opposite side [11]. The process was combined with fine blanking, and the material flow and fracture were investigated with numerical simulations and experiments [12]. It can be observed that, due to the punch penetration into sheet metal, the deformation condition is different from that of extrusion forging. Press forging process has been used to manufacture thin-walled cases, with bosses, of electronic devices from magnesium alloys [13,14]. Variations of this process were developed to manufactured stepped holes [15] and rib and boss features [16]. The surface features created by these processes were isolated protrusions unlike the desired surface feature of a pin fin array.

This paper discusses a preliminary study on manufacturing of low profile pin fin array on sheet metal. The experimental and simulation techniques for extrusion forging of aluminum sheet are presented, and the results are shown and discussed. To reduce the forming force and increase the production rate, the simulation work is extended to extrusion rolling that has not been previously studied.

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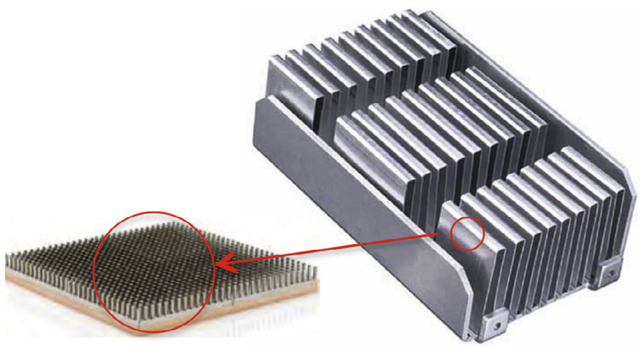

Fig. 1. Low profile pins on folded fin heat sink [1,2].

2. Method

To examine the feasibility of manufacturing the pin fin array feature on sheet metal surface, tooling was designed and made to perform extrusion forging experiments. A punch with 10 × 10 cavity pattern is shown in Fig. 2a. The hole diameter was 1.0 mm and the spacing between the centers of the holes was 1.5 mm. With this punch, a specimen obtained from the extrusion forging experiment is shown in Fig. 2b. A second punch has a 3 × 3 cavity pattern. This smaller punch can produce higher pressure and generate taller bosses as shown in Fig. 2c. The shock-resistant, air-hardened S7 tool steel was chosen as the tooling material. A plunge EDM with a small diameter electrode rod was used to drill the holes. The workpiece materials were aluminum 1100 sheets with different thicknesses (0.5 mm, 0.8 mm and 2.0 mm). Tensile tests were conducted to obtain the material properties, including: elastic modulus $E = 68.46$ GPa; yield strength $s_y = 20.9$ MPa; work-hardening exponent $n = 0.26$. In the experiment, the displacement of the punch was tracked. After stopping the punch motion, the specimens were pulled out and the boss height was measured.

Efforts were also made to conduct finite element forming simulation to acquire additional insights of the processes. The commercial software ABAQUS was used. To reduce computational time, a *unit cell* (the marked square in Fig. 2b) in forming a single protrusion was modeled. As shown in Fig. 2d, the unit cell consists of a single cavity punch, a unit flat surface die, and a unit workpiece. The punch and die were modeled as rigid body. The workpiece was modeled as elastic-plastic material with the data from tensile tests. The eight-node linear brick, reduced integration, hourglass control element (C3D8R) was used to mesh the workpiece. To address mesh distortion concerns, the Arbitrary Lagrangian Eulerian (ALE) adaptive meshing was employed. The values of various shear friction factor was assigned. In the simulation, the use of the unit cell to represent the extrusion forging of the entire workpiece can be justified with appropriate boundary condition. Since the unit cell is an isolated but repetitive unit of the whole model, other than those cells near the edges of the workpiece, the cell boundaries are the lines of symmetry. As such, it is reasonable to prescribe a symmetry boundary condition that allows the material to move in the vertical direction only. The explicit dynamic solver was employed with mass scaling and time scaling to reduce computation time. The scaling factor was selected based on the criterion that the ratio of kinetic energy (ALLKE) to the total internal energy (ALLIE) is less than 5%.

3. Results and discussion

The boss height, h, with respect to the punch displacement, d, was investigated. Base on volume consistency, the boss height can be calculated analytically:

$$h = \frac{4s^2 d}{\pi D^2} \quad (1)$$

where s is the length and width of the square prism unit cell and D is the diameter of the boss. From Eq. (1), the boss height expressed as a function of punch displacement is shown in Fig. 3a. The experimental results for $t = 0.5$ mm are also plotted. Also in the figure are two lines obtained from numerical simulations. The line "constrained boundary" represents the results from the boundary condition that the material can only move in the vertical direction as described previously. The line "free boundary" indicates that the lateral displacements are allowed as in extrusion forging of a billet. It can be observed that experimental curve initially followed the free boundary curve and turned towards the constrained boundary curve at the punch displacement around 0.12 mm. While the experimental curve stopped at $d = 0.14$ mm due to the limited press capacity, it is clear that the experimental results would approach the constrained boundary line if the specimen is further compressed. It can also be observed that the analytical line is below the constrained boundary line. As shown in the deformed geometry in FEA (Fig. 3a), the prediction of taller boss is mostly due to that the top of the boss was not flat.

Fig. 3b shows the plot of average pressure versus boss height for specimen thicknesses, t, of 0.5 mm, 2.0 mm, and 10.0 mm. The average pressure was calculated from the punch force divided by the punch-specimen contact area. It was found that the curves resemble a polynomial function. There were two concerns observed from the simulation. First, a back cavity, shown in the FEA (Fig. 3b), was formed when the boss height reached a certain

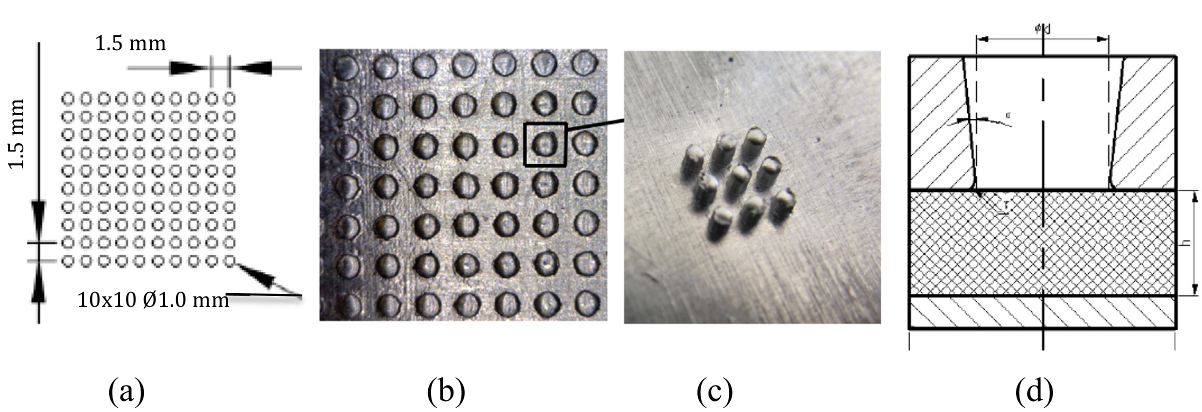

Fig. 2. (a) 10 × 10 pin fin pattern (b) specimen of 10 × 10 pattern (c) specimen of 3 × 3 pattern, and (d) unit cell configuration.

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