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Technical paper

Simulations and experiments in punching spring-steel devices with sub-millimeter features

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ABSTRACT

This work demonstrates the feasibility of meso-scale (100 μm to mm) punching of multiple holes of intricate shapes in metals. Analytical modeling, finite element (FE) simulation, and experimentation are used in this work. Two-dimensional FE simulations in ABAQUS were done with an assumed material modeling and plane-strain condition. A known analytical model was used and compared with the ABAQUS simulation results to understand the effects of clearance between the punch and the die. FE simulation in ABAQUS was done for different clearances and corner radii of the punch, die, and holder. To complement modeling with real experiments and for the purpose of comparison, a set of punches and dies were made to punch out a miniature spring-steel gripper. Comparison of compliant grippers made by wire-cut electro discharge machining (EDM) and punching shows that realizing sharp interior and re-entrant corners by punching is not easy to achieve. However, the promise of realizing meso-scale parts with complicated shapes through punching is demonstrated in this work; and further work is identified and some strategies are suggested for improvement. The main contribution of this paper is in adapting the well-established punching and blanking operations to the meso-scale as a viable alternative to making miniature devices currently dominated by lithography-based techniques.

1. Introduction

Despite significant advances in silicon microfabrication processes, economical production of low-volume microsystems devices is not viable. Silicon remains the choice material relying on lithography and cleanroom techniques [1]. However materials and processing are prohibitively expensive in silicon-based fabrication if the number of wafers to be processed is low. Packaging of silicon devices is also expensive. Polymers and metals are therefore good alternatives. Although polymer processing is increasingly used, metals are not used as much. Metals have an advantage over polymers in applications where high stiffness, force, and strength are desired. Metals, if processed to create micro- or meso-size features by batch production, pave the way for low-cost packaged micro devices that are comparable in size and performance to packaged silicon- and polymer-based miniature devices. Therefore, the premise for this work is that adapting macro-scale manufacturing techniques such as sheet metal bending, forming, and punching to the meso-scale may help realize miniature devices in metal. Thus, the objective of the work is to investigate the lower limits of feature sizes that can be obtained in punching and blanking techniques, which are economical and fast.

Meso-scale (100 μm to mm) metallic parts can be manufactured by various processes such as spark erosion, electro-chemical machining (ECM), wire-cut electro-discharge machining (EDM), extrusion, forming, punching and blanking, milling, and turning. Of these, punching and blanking are amenable for economical and fast batch-production. Consider a metallic XY precision stage shown in Fig. 1 [2]. It was made using wire-cut EDM. It took a long time (more than two days) with this process because of the complicated shapes and long edges that need to be cut out of a sheet metal or a thin foil. Punching out multiple intricately shaped holes in a few stages is an option. In this work, we explore if such a multi-stage punching operation is possible so that miniature sensors, actuators, and mechanisms can be made out of spring-steel.

There is a lot of literature on modeling punching processes in various materials from metals to rocks. Much of this work is aimed at punching large features (e.g., parts of machinery) and small but simple shapes (e.g., those required in microelectronics devices). Limited guidelines exist to understand, for example, how narrow a beam (see Fig. 2a) can be punched and how to design the punch and the die along with suitable clearances. The situation becomes worse when the shapes of the punched holes become intricate as shown in Fig. 2b where a compliant gripper [3] needs to be realized by means of punching. We briefly review some of the earlier work to indicate the state-of-the-art in this field.

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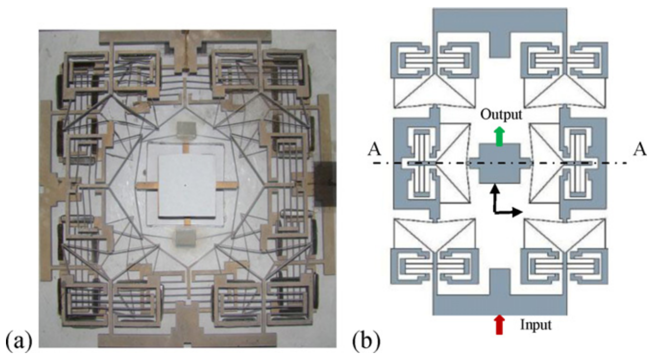

Fig. 1. (a) A two-layered XY-precision stage cut out of a spring-steel sheet using wire-cut EDM [2]. (b) One layer of the stage.

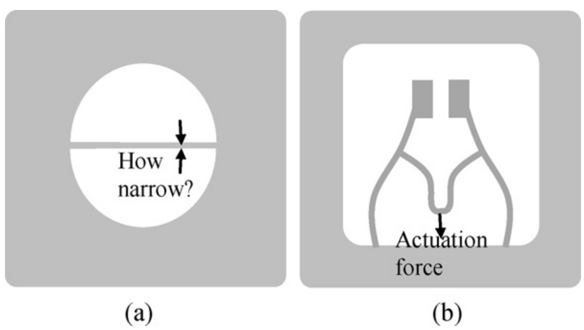

Fig. 2. (a) A narrow beam to be realized by punching closely spaced two semicircular holes and (b) a compliant gripper that also requires two holes to be punched but those with complicated shapes, leaving out curved beams of narrow width. The gripper in (b) works by elastically deforming upon application of the actuation force as shown by the arrow.

It appears that there has been no focused effort until now in meso-scale punching and blanking of shapes as complicated as the ones shown in Fig. 2b although there are some related questions that are addressed. For instance, Shin et al. [4] analyzed the problem of minimizing burr-height in meso-scale punching operations by using a closed-loop system and ultra-precision adjustment. They note that work in this field began as early as 1950s (e.g., Chang and Swift in 1950 [5]). More recently, Hambli [6] used neural networks to predict the burr height.

There is also related work in understanding shear fracture in punching processes [e.g., 7–15]. In one of the earliest works on this problem, Atkins [7] presented criteria for initiation of cracks and their propagation as well as conditions for multiple cracking in punching processes. Ghosh and co-workers [8–10] presented analytical and computational modeling of punching and blanking operations and derived guidelines for clearances between the punch and the die. Refs. [11,12] concluded that punching process should be analyzed using mixed-mode fracture, particularly in I and II modes. Finite element (FE) simulations of sheet metal forming were reported in [13,14]. Klingenberg and Singh [15] presented theoretical models for punching by assuming 2D deformation and its experimental verification.

While the aforementioned studies were done in view of macro-size punching, micro punching technology was reported in [16–18] where multiple holes of 2–10 μm diameter and triangular and hexagonal shapes with a side length of 200 μm were made. Although punching numerous micro-sized holes along the edges of complicated shapes such as the ones in Fig. 2b may be possible, here, we want to explore if it can be done using just a few punched shapes of intricate shapes because it is fast and it is easy to control burr and thus ensure the smoothness of cut-surfaces.

The rest of the paper is organized by first presenting preliminary attempts at punching simple shapes to understand the problems involved and to compare with commercially available craft-punches for creating varied shapes in paper and thin cardboard. It is then followed by presenting an analytical model previously reported in the literature and examining whether it can be validated using finite element analysis (FEA). If it is validated, some guidelines can be established for punching complicated shapes. Also included in the paper is an attempt at punching a spring-steel gripper with three stages of punching followed by spark erosion and then comparing the results with a specimen that is wire-cut with EDM. Some concluding remarks are mentioned in the last section.

2. Preliminary attempts

Consider the simple case of punching a circular hole in paper and thin foils. Shown in Fig. 3a is a hand-operated punch tool. It is desirable if such a hand-held tool has a die that can cut out, either in one step or progressively with several punches, a compliant gripper of the kind shown in Fig. 2b. It will then be possible to make as many miniature grippers as needed without any overhead other than making the punch and the die. As an initial experiment, we made a square punch and die using which square holes of about 5 mm side were punched in cardboard paper, plastic film and aluminum foil. It is apparent from Fig. 3b that the quality of the edges is not good. It depends on the alignment between the punch and the die, their sharpness and hardness, and the accuracy of their shapes.

For comparison, we used a craft-punch that is capable of punching intricate shapes in paper and thin cardboard. Shown in Fig. 4a and b are the inner parts of a pair of such punches. Fig. 5a–d shows samples of 0.150 mm thick paper and aluminum foil of less than 0.025 mm thickness. It can be seen that the edges of the paper specimen (see Fig. 5c and d) are better than those of aluminum specimens, which show slanted edges and wrinkles caused by the process of punching. While this shows that intricate shapes can indeed be punched, it also highlights the point that punching metal (however thin it is) has some issues to be investigated.

A number of issues need to be resolved in realizing the goal of punching out the entire compliant gripper (see Fig. 2b) and other similar devices (see Fig. 1) from a thin spring-steel sheet of

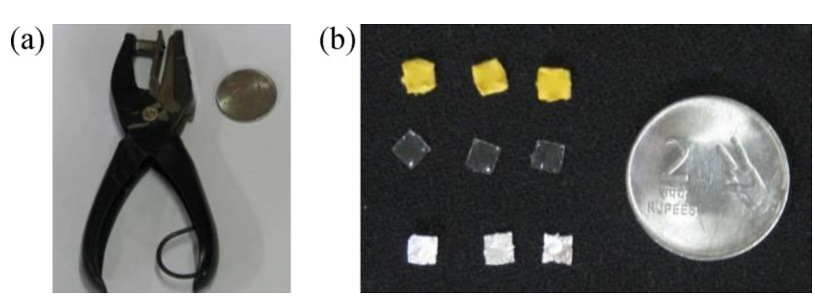

Fig. 3. (a) A punching hand-tool retrofitted with custom-made punches. (b) Blanked out squares of, from to bottom: cardboard, plastic film, and aluminum foil.