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# Experimental and numerical investigation on micro deep drawing process of stainless steel 304 foil using flexible tools

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ABSTRACT

Flexible forming technology provides significant application potential in various areas of manufacturing, particularly at a miniaturized level. Simplicity, versatility of process and feasibility of prototyping makes forming techniques by using flexible tools suitable for micro sheet metal forming. This paper reports the results of FE simulation and experimental research on micro deep drawing processes of stainless steel 304 sheets utilising a flexible die. The study presents a novel technique in which an initial gap (positive or negative) is adopted between an adjustment ring and a blank holder employed in the developed forming system. The blank holder is moveable part and supported by a particular spring that provides the required holding force. The forming parameters (anisotropy of SS 304 material, initial gap, friction conditions at various contact interfaces and initial sheet thickness) related with the forming process are in details investigated. The FE models are built using the commercial code Abaqus/Standard. The numerical predictions reveal the capability of the proposed technique on producing micro metallic cups with high quality and large aspect ratio. To verify these results, number of micro deep drawing experiments is conducted using a special set up developed for this purpose. As providing a fundamental understanding is required for the commercial development of this novel forming technique, hence the optimization of the initial gap in accordance with each sheet thickness, thickness distribution and punch force/stroke relationship are detected.



## 1. Introduction

Remarkable development in micro forming technology and relevant industries has been noticed through the last decade, mainly due to the increasing demand on high quality portable electronics and other mini/micro devices [1–5]. This demand has remarkably attracted a great attention from researchers [5–7]. Owing to provide fundamental understanding of the micro forming technology, substantial research activities have therefore been published during the last decade [2,8]. Several significant potential advantages can be gained from using flexible tools in sheet metal forming processes; such as low-production cost, eliminating alignment difficulties, producing complex-shaped parts. The workpieces taken from pre-polished or painted sheet metals can be formed without using any protective coating as they. These issues make flexible forming technology very appropriate for micro sheet metal forming [6,9,10].

To clarify the essential fundamental characteristics of this technology, several research studies have been conducted. Quadrini et al. [11] investigated flexible forming process of thin aluminium alloy sheets to produce simple shapes. Different rubber materials were used for the forming tools. It was found that the harder rubber pad improved the drawability of the blank material. Peng et al. [12] presented an experimental and numerical investigations on micro sheet metal forming of stainless steel foil using a soft punch. The effects of the process parameters of sheet grain size, rubber hardness and friction coefficients were also investigated. Dirikolu and Akdemir [13] established a 3D finite element (FE) model for flexible forming process of sheet metal. The rubber hardness and blank material properties were the main parameters in this work. As a result, it was shown that the FE method was effective tool in process design. Ramezani et al. [9] optimized theoretical approaches that can be used to simulate the static and kinetic friction at the blank and its interfaces in rubber-pad forming process. Their study showed that the use of the static friction model resulted in highly accurate predictions for the punch load while the kinetic friction model provided good results at higher forming velocities. A novel microscale laser dynamic flexible forming (μLDFF) technique is presented by Wang at el. [14]. Numerical simulations and experiments were carried out to investigate the key process parameters. The results showed that the deformation depth of the thin metal sheets decreases with the increase in the thickness of the soft punch. Also,

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it was found that increasing the laser pulse energy resulted in an increase in the deformation depth of formed workpiece.

Recently, the experience-based knowledge of the micro-forming process parameters is not sufficient, particularly when flexible tools are utilised, thus more investigations and improvements on this technology are imperatively needed [12]. In this paper, micro deep drawing of stainless steel (SS304) foil using a polyurethane rubber flexible forming pad, 63 Shore A hardness, is evaluated through experiments and numerical simulation. The foil work-pieces used in the experiments were each 10 mm in diameter and with varying thickness as follows: 60 μm, 100 μm and 150 μm. The numerical simulation was achieved using finite element analysis (FEA) model, built using the commercial code Abaqus/Standard. The main purpose of this study was to demonstrate the influence of blank material anisotropy, initial blank thickness, initial gap, and friction coefficient on the forming process. The experimental results show a good correlation with that obtained from the numerical simulations, in terms of geometrical aspects of the final products, thickness distributions and punch load-travel relationships.

## 2. Experimental methodology

### 2.1. Characterization of material behaviour

Stainless steel 304 is used widely in various industrial applications, especially in the manufacture of micro device components. Therefore, the workpieces used in this study are intended from SS304 sheets with 60 μm, 100 μm and 150 μm in thickness. In order to evaluate the effect of the anisotropic behaviour (due to the rolling operation), dogbone-shaped specimens are cut along rolling, diagonal (45°) and transverse directions from each thickness. The dimensions for the testing specimens are determined from the ASTM E8 standard as shown in Fig. 1b. The tensile tests are performed using an Instron 5969 machine with 50 kN load cell with velocity of 0.1 m/s. A non-contacting advanced video extensometer (FOV 200 mm) is utilized for measuring the longitudinal and transverse strains of the sheet specimens during the tensile test. Fig. 1a presents the stress–strain relationships obtained of the tensile tests for the SS304 foils with the thicknesses 60 μm, 100 μm and 150 μm at rolling direction. The mechanical properties of SS 304 sheets are listed in Table 1, which generally agree with the results obtained by Saotome [5].

### 2.2. Compression tests of rubber material

In order to define rubber material behaviour in the FE model, the mechanical properties obtained from uniaxial and volumetric compression tests are utilized. The hyperelastic coefficients of the rubber 63A material were obtained via the uniaxial compression test carried out in accordance to the ASTM D575 standard. Sandpaper sheets were placed at specimen and machine platens interfaces to resist lateral slippage of the rubber surfaces, as in Fig. 2b. The engineering stress–strain relationship obtained from the uniaxial compression test can be seen in Fig. 2a. Regarding the material compressibility factor ($D_1$), a volumetric compression test is achieved here using the device illustrated in Fig. 3a. The very small clearance is to ensure that the rubber specimen used will be restricted perfectly and there is no space for the rubber to extrude through during the test [15]. The relationship between pressure and volume ratio that is obtained from the volumetric compression test is illustrated in Fig. 3b. The results of the uniaxial and volumetric compression tests mentioned above were used as input data in the code ABAQUS/Standard to obtain the material coefficients of rubber 63A shown in Table 2.

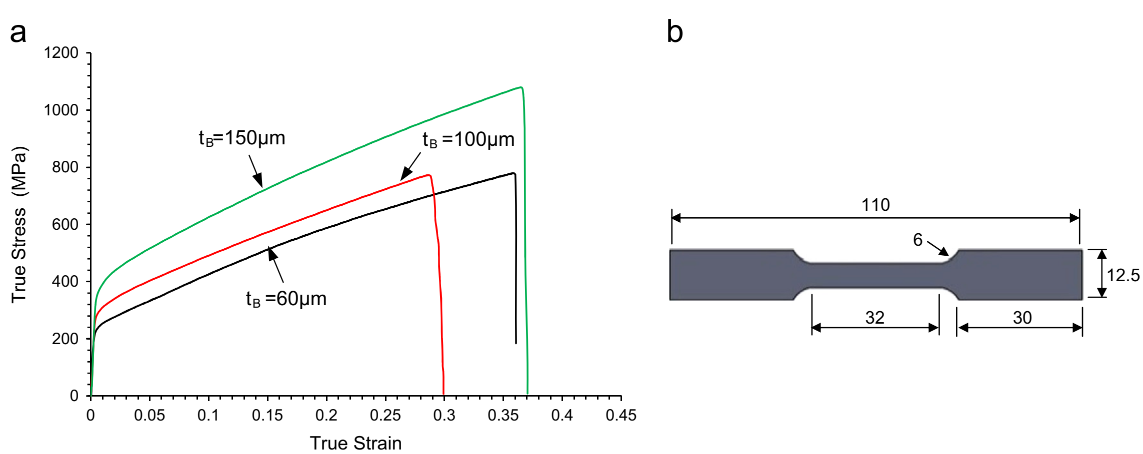


**Fig. 1.** (a) Engineering stress–strain relationships along rolling direction (b) tensile test sample.

**Table 1**
Mechanical properties of SS304 foils.

| Thickness $t_B$ (μm) | Angle to rolling direction (°) | Young modulus $E$ (GPa) | Yield point $\sigma_o$ (MPa) | Tensile strength $\sigma_{ult}$ (MPa) | $K$ (MPa) | $n$ |
|---|---|---|---|---|---|---|
| 60 | 0 | 128.6 | 225.4 | 545 | 1252 | 0.4684 |
| | 45 | 192.7 | 273.2 | 568 | 1290 | 0.4288 |
| | 90 | 179 | 209.8 | 554.6 | 1299.7 | 0.4413 |
| 100 | 0 | 154.5 | 277.2 | 580.5 | 1350.7 | 0.4516 |
| | 45 | 197 | 252.3 | 539 | 1269.9 | 0.4340 |
| | 90 | 166 | 287.3 | 621.8 | 1400.2 | 0.4103 |
| 150 | 0 | 107.5 | 373 | 749.8 | 1698.2 | 0.4522 |
| | 45 | 120.2 | 327.4 | 730.7 | 1585.5 | 0.4159 |
| | 90 | 156.8 | 316.2 | 662 | 1504.6 | 0.4260 |