International Journal of Mechanical Sciences 148 (2018) 263–271

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Microcoining ripples in metal foils

Greg C. Randall[a,*], Jinesh Dahal[c], James Vecchio[a], Shashank Agarwal[b], Rounak Mehta[b], G. Ravichandran[b], Aaron P. Stebner[c]

[a] General Atomics, 3550 General Atomics Ct., San Diego, CA 92121, USA
[b] Caltech, 1200 E California Blvd., Pasadena, CA 91125, USA
[c] Colorado School of Mines, 1500 Illinois St., Golden, CO 80401, USA

A R T I C L E I N F O

Keywords:
Coining
Plasticity
Contact mechanics
Indentation
Work hardening

A B S T R A C T

Experiments, upper bound models, and finite element simulations are used to determine forming loads needed to microcoin surface ripples in thin metal foils. Coining is traditionally performed in a closed die, however enclosing all non-patterned surfaces is difficult to directly scale down to sub-millimeter foils. We find different forming regimes can exist at this small scale in an open pressing configuration. We explore the effects of the metal foil thickness and its work hardening behavior, two primary factors controlling the microcoining ripple forming load. For very thin foils, the load needed to coin a ripple pattern is lower than the load needed to compress the foil so that the open pressing configuration behavior is effectively closed with pattern formation without thickness change. For moderate thickness foils, the load needed to coin significantly drops as the entire foil compresses. For thick foils approaching bulk materials, the pattern will not completely form as the die macroscopically indents into the metal. Work hardening is found to raise the forming load for the thin, effectively closed die scenario, however it is a secondary effect at moderate thickness. This insight is used to microcoin patterns in extremely hard, thin metal foils.

1. Introduction

Coining is an age-old process well-known for requiring large pressures to suitably form a pattern or image in the surface layer of a metal flat [1,2]. From a metallurgical perspective, coining represents a method to alter surface topology and tribological conditions. Loads required for pattern formation are known to depend on friction and the geometry of the workpiece elastic-plastic boundaries. Early coining studies considered flow into single impressions or corners in a closed die [2–5]. These closed die, large single feature coining models and experiments showed a steep rise in mean forming pressure p_m as pattern transfer approached unity ($p_m/Y \sim 4$–10, where Y is the flow strength, or in these references, the yield strength of a non-work hardening material). Forming loads were shown to significantly decrease by coining with an open die geometry so that the workpiece was allowed to plastically flow simultaneously in a direction away from the coining feature [1,6–11]. In this scenario, a shear-free "neutral plane" exists within the workpiece dividing the flow into the coining feature from the flow to the outside of the die. Generally speaking, replacing elastic-plastic high-shear boundaries with neutral planes should lower the required loads driving the plastic flow. In experiments on an aluminum bar, the forming pressure to coin a corner recess reduced from $p_m/Y \sim 4$ to $p_m/Y \sim 2$ just by adding a relief hole in the center of the die so that metal flows both into the corner gap and into to the open hole [7].

In addition to the single feature coining studies in open and closed dies, there have been studies on contact and deformation of rippled metal surfaces. A ripple with amplitude A much smaller than wavelength λ is a common model used to understand rough surfaces [12]. The two analogous problems of crushing a rippled surface or imprinting ripples into a flat surface have been studied to predict the fractional area of contact α. Moore [13] and Greenwood and Rowe [14] found that asperities in a crushed metal cylinder's flat surface were only smoothed if the cylinder was short enough for the plastic zone to extend through the entire workpiece thickness. Ripple pattern analysis followed with the goal of trying to quantitatively determine the area of contact for a given mean load pressure p_m deforming a rippled surface [12,15–25]. When the workpiece was constrained, the plastic flow in the ripple region was found to be similar to inverse extrusion and a steep rise in p_m was needed to create a high area of plastic contact [12], typically $p_m/Y \sim 4$. In addition, a limiting fractional contact area was found to be $\alpha \sim 1/2$ in unconstrained or indentation-like contact [16,17,20]. Of note, Ike and Makinouchi performed finite element simulations showing the large differences in asperity flattening in lateral compression (to mimic a constrained closed die) versus lateral tension (to mimic an open die scenario) [23]. Like in the open vs. closed coining research above,

* Corresponding author.
E-mail address: randall@fusion.gat.com (G.C. Randall).

https://doi.org/10.1016/j.ijmecsci.2018.08.034
Received 26 May 2018; Received in revised form 23 August 2018; Accepted 28 August 2018
Available online 29 August 2018

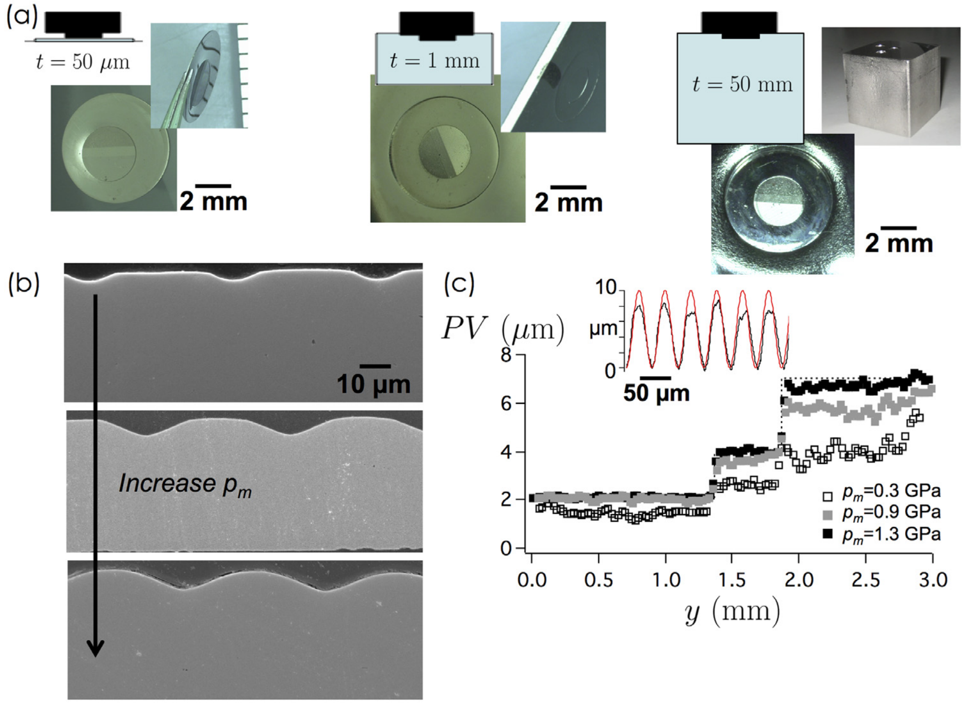

Fig. 1. (a) Images of coined metals of different thickness, 50 μm, 1 mm, and 50 mm (b) Cross-section SEM images of metals coined at increasing load p_m (c) Example of peak-to-valley distance PV of the coined metal obtained from a central lineout from a die patterned with three amplitudes. Inset shows a portion of a $\alpha = 0.67$ coining run with the ideal $A = 5.0$ μm, $\lambda = 50$ μm die pattern superimposed.

they observed the forming pressure to fully flatten the asperities to drop to $p_m/Y \sim 2$ in mild steel when mimicking an open die.

Fueled by the portable microelectronics device market and growing nano- and micro- research trend [26,27], researchers have recently developed microcoining to coin microfeatures into sub-millimeter-sized foils [9,28–34]. Initial microcoining work focused on engineering die materials. First, softer metals were microcoined with silicon dies [9,28–30]. Then stronger dies were made in tool steel [32] or nitrided steel dies that could be precision diamond turned [33–35] in order to microcoin harder metals ($Y \sim 300$ MPa, where Y is the flow stress) like stainless steel or tantalum. However, due to these die limitations, no microcoining has been performed on extremely hard metals with $Y > 1$ GPa. The specific application for this later work has been to microform ripple patterns for materials science laser-induced compression studies [36–38]. To field these targets, the fabrication teams must adjust forming conditions for different metal foil types and dimensions. There are some important differences that distinguish microcoining from standard coining. First, size-dependent or texture-dependent plasticity effects can induce non-uniform deformation because the local microscale yield stress may vary [26,27]. In addition, formability effects can arise due to the relation between a strain gradient length scale and the metal and die geometry [9]. Practically, a sub-millimeter metal workpiece is difficult to fully contain in a closed die traditionally needed for coining precision. This last point will be the focus of this study as all microcoining work referred to here can be considered similar to embossing [29], i.e. unconstrained or in an open die configuration. Studies have shown deviations in ripple forming loads larger than expected from microforming texture variations when varying the material source and thickness [34].

Based on these observations of highly sensitive microcoining forming loads and the need to pattern $Y > 1$ GPa materials, the goal of this work is to predict and experimentally determine microcoining loads required for ripple patterning in thin foils of different mechanical properties and dimensions. In particular we will look at low vs. high work hardening materials and the effect of metal foil thickness (Fig. 1 (a)). As depicted in Fig. 1 (b), we show experimental coining results of pattern transfer progression with increasing applied pressure p_m. Upper bound models and finite element simulations are used to probe the plasticity details. A key element to the ripple microcoining problem is deformation on two length scales: the macroscale problem at the length scale of the die R_{die} and the microscale problem at the ripple wavelength λ. The metal's thickness t plays a key role in the interplay of these length scales. We will show that closed die containment is not required for precise patterning in thin foils because the patterns form as if effectively closed. Furthermore, coining loads can be significantly reduced if a small compression is allowed so that open die through-thickness plasticity is achieved. We will use this insight to expand the microcoining process to extremely hard materials with a $\sim$GPa flow stress.

2. Calculations: Upper bound models

Microcoining a ripple pattern into a thin metal entails a study of two problems on different length scales: compression of a thin metal foil on the R_{die} scale and an inverse extrusion of metal into the die ripples on the λ scale. In the following, we will use Kudo's version of upper bound theory [39] to review the forming pressures for thin foil compression, and offer predictive models for closed and open die ripple coining. All upper bound model equations in this section are derived step-by-step in the Supporting Information. Briefly, each calculation requires approximating the plastic flow field as an assembly of unit rectangles with either smooth or full-friction boundaries (with each rectangular region composed of rigid-triangular velocity fields as detailed in Ref. [39]), calculating the total energy dissipation, and minimizing the total energy dissipation with respect to the geometric parameters of the plastic flow field (i.e. unit rectangle properties).

By comparing the load required to compress the thin foil with the load required to coin, we can construct a microcoining operating plot as a function of the foil thickness shown in Fig. 2(a). In the following section we explain the creation of this operating plot. We will use a rigid-plastic analysis, which should be valid when $\alpha AE^*/\lambda Y > 0.1$ [24,40], where E^* is the reduced Young's modulus, Y is the yield stress, and