International Journal of Mechanical Sciences 71 (2013) 58–67

Contents lists available at SciVerse ScienceDirect

International Journal of Mechanical Sciences

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

Optimization of axisymmetric open-die micro-forging/extrusion processes: An upper bound approach

Ehsan Ghassemali [a,b,*], Ming-Jen Tan [a], Anders E.W. Jarfors [c], S.C.V. Lim [d]

[a] School of Mechanical & Aerospace Engineering, Nanyang Technological University, Singapore 639798
[b] Singapore Institute of Manufacturing Technology (SIMTech), 71 Nanyang Dr, Singapore 638075
[c] School of Engineering, Jönköping University, P.O. Box 1026, SE-551 11 Jönköping, Sweden
[d] Materials Engineering, Monash University, Wellington Road, Clayton, Victoria, Australia

ARTICLE INFO

Article history:
Received 28 August 2012
Received in revised form
12 March 2013
Accepted 15 March 2013
Available online 25 March 2013

Keywords:
Upper bound theory
Process optimization
Initial blank shape
Neutral plane
Microforming

ABSTRACT

There is a trend towards component miniaturization and strong drive towards cost effective and sustainable metal forming techniques of miniaturized components. This paper presents an upper bound solution for the optimization of open-die forging/extrusion processes in the forming of micro-pins from a sheet metal. Using such an analytical modeling approach, the critical blank thickness, the resulting final part geometry, together with the required forming load were predicted based on the location of the neutral plane under the punch during the process. Based on the phenomenological findings of the process, the geometry size factor, *x*, was introduced explaining its relative importance to the model. Experimental results obtained from C11000 copper samples using a progressive microforming process was found to agree well with the results predicted by the model. The results were also validated with other results reported before from a similar process.

1. Introduction

1.1. Modeling techniques

To obtain an accurate solution for a metal forming process requires a deep knowledge of the influence of different parameters such as material properties, tribological conditions, tool geometry and velocity. The characterization of the interaction between these parameters is also necessary for process optimizations, which can be accomplished easier through modeling techniques. Indeed, the objective of the modeling is mainly to save time and reduce the costs by eliminating or minimizing trial-and-error tests for process design [1–3].

A variety of different modeling methods have been used to find solutions for real problems in metal forming processes that includes finite element modeling (FEM), slip-line field theory, and upper/lower bound analysis (limit analysis).

Although FEM provides an accurate and visual description of material flow, stress and strain distribution during the process, it requires considerable amount of computing time [4]. More importantly, FEM is unable to provide a so-called universal solution, and it needs to be conducted for each specific condition on case by case basis. For the slip-line theory, it is more complicated and has mostly been successful only in analyzing plane-strain conditions.

In comparison, the limit analysis has proven to be a powerful method to simply and quickly provide universal solutions within reasonable engineering approximations [5]. Two solutions have been developed in this method: upper bound, and lower bound. Generally, the exact required forming power is located between the power predicted by upper bound and lower bound analysis. However, the stress-based lower bound solution is usually more difficult to develop. Furthermore, for an upper bound solution, the actual required forming load is never higher than the predicted load. Thus, it is more practical for metal forming analysis [6].

1.2. Upper bound theorem

The upper bound technique not only predicts the required forming load, but also has the capability of process optimization, and can be used for understanding the material behavior during the forming processes. Avitzur [5] used upper bound analysis for the calculation of the forming power and prediction of flow pattern in a ring compression test [7]. The effect of friction and geometrical conditions on the material flow [7] and forming pressure [6] was investigated in the ring compression test [8], developing the concept of the neutral plane or "no-slip circle" which was introduced previously [9]. It is to be noted that Kudo [9] did not consider the effect of material flow inside the die orifice on

* Corresponding author at: School of Mechanical & Aerospace Engineering, Nanyang Technological University, Singapore 639798.
Tel.: +65 84312143.
E-mail addresses: ehsa0005@ntu.edu.sg, ehsan.ghassemali@gmail.com (E. Ghassemali).

0020-7403/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijmecsci.2013.03.010

Nomenclature

C	constant value
h	pin height (mm)
J^*	upper bound on energy consumption rate; applied power (J/s)
J^*_e	extrusion component of the rate of energy loss (J/s)
J^*_r	ring compression component of the rate of energy loss (J/s)
L	die land length (mm)
m	friction factor
P	pressure (N/mm^2)
R	radial position (mm)
R_0	punch radius (mm)
R_i	die orifice radius (mm)
R_n	neutral plane radius (mm)
S_L	area of velocity discontinuity (mm^2)
S_t	surface over which tractions are prescribed (mm^2)
T	blank thickness (mm)
T_i	prescribed applied surface tractions (mm^2)
Δt	time difference (s)
V	volume (mm^3)
Δv	velocity difference (m/s)
v_i	velocity component (m/s)
v_p	punch velocity (m/s)
$\dot{W}_f$	frictional rate of power loss (J/s)
$\dot{W}_i$	internal rate of power of deformation (J/s)
$\dot{W}_s$	shear rate of power loss (J/s)
x	geometry size effect factor
y	vertical position (mm)
$\dot{\varepsilon}_{ij}$	strain rate component (1/s)
θ	angular position
$\sigma 0$	effective flow stress (N/mm^2)
τ	shear stress (N/mm^2)

the overall energy loss during the so-called heading process. Avitzur [5] did however consider the effect of material flow inside the die orifice for the conventional extrusion process.

Later, Agrawal et al. [10] used the upper bound approach for optimization of the blank thickness in a deep drawing process. This is an important aspect of deep drawing process, since it could minimize the earring defect and also decrease the required drawing force. The limit analysis technique was also used similarly to optimize the stamping process [11].

1.3. *Phenomenological studies for the modeling*

To optimize a forming process using modeling techniques, a phenomenological investigation of the material behavior during the process is needed [12].

Discussing about the open-die forging/extrusion or “heading” process, Vickery and Monaghan [13] reported that the process has three stages. In Stage I, the process is similar to the compression of a cylinder with little or no extrusion through the die orifice. During this stage the material only flow outwards from the central axis. In Stage II, the extrusion begins. During this stage, the total height of the pin remains almost constant while the flange thickness continues to reduce. Thus, there is a balance between forging and extrusion phenomenon in the process. In Stage III, extrusion is the dominant flow process and material prefers energetically to flow inside the die orifice rather than outwards. The same phenomena have been reported by Ghassemali et al. [14], for a progressive forging/extrusion process on a sheet metal.

Consequently, there must be a critical blank thickness after which the extrusion is the dominant phenomenon, in this type of metal forming process. This can be used to successfully optimize the axisymmetric sheet metal forming processes, to reduce the material wastage and also the required forming load. This has not been reported to date, to the authors' knowledge.

The initiation of each stage in the process is defined by the location of the neutral plane. Indeed, the open-die forming processes can be controlled precisely by investigating the location of neutral plane during the process. As initially discussed by Avitzur and Sauerwine [15], the location of neutral plane is a function of the blank geometry and friction conditions [12]. It is worth noting that by changing the blank thickness, the location of neutral plane changes to minimize the overall required energy for forming process [16].

The aim of this work is to develop a model to provide a universal solution for design optimization of the axisymmetric open-die forging/extrusion processes, using upper bound theorem. Through this, one can theoretically predict the forming load, critical blank thickness and the final part dimensions in the process. To do so, after analyzing different phenomena occurring during the process, by means of the precise prediction of the neutral plane location during the process, the required parameters were modeled. The effect of punch-to-die diameter ratio was investigated, considering the geometry size factor (x), which will be defined in greater details in subsequent sections. A progressive micro-pin-forming process was used to validate the model, as well as the results from similar previous studies. All these works were reported in dry friction condition.

2. Theoretical derivation

2.1. *Upper bound basics*

A review and description in detail of the upper bound theory can be found in [5]: “Among all kinematically admissible strain rate fields, the actual one minimizes the below expression”

$$J^* = \dot{W}_i + \dot{W}_f + \dot{W}_s$$

$$J^* = \frac{2}{\sqrt{3}}\sigma_0 \int_V \sqrt{\frac{1}{2}\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}}\, dV + \int_{S_L} \tau|\Delta v| ds - \int_{S_t} T_i v_i \, ds \tag{1}$$

Basically the actual required forming power J^* is never higher than that computed by using Eq. (1). The first term ($\dot{W}_i$) represents the internal power of deformation over the volume of deforming material. The second term ($\dot{W}_f$) expresses the shear power over surfaces of velocity discontinuities including the tool–material interfaces. Friction stress is prescribed as constant shear stress

$$\tau = \frac{m\sigma_0}{\sqrt{3}} \tag{2}$$

The friction factor m is taken as constant for a given die and material under constant surface and temperature conditions. The maximum shear a material can withstand according to von-Mises yield criterion is $\sigma_0/\sqrt{3}$, meaning that the limits of m are $0 \le m \le 1$.

The last term in Eq. (1), $\dot{W}_s$, includes the power supplied by body tractions, such as back stress applied in the wire drawing or back and front tensions in rolling processes.

To simplify the calculation procedure in upper bound approach, the block elemental technique (BET) was introduced by Kudo [9] and developed by Avitzur [5]. This technique involves the subdivision of the deforming material into basic elements. The velocity