International Journal of Mechanical Sciences 138–139 (2018) 524–536

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Analysis and modelling of a novel process for extruding curved metal alloy profiles

Wenbin Zhou[a], Jianguo Lin[a,*], Trevor A. Dean[b], Liliang Wang[a]

[a] Department of Mechanical Engineering, Imperial College London, London SW7 2AZ, UK
[b] Department of Mechanical Engineering, University of Birmingham, Birmingham B15 2TT, UK

ARTICLE INFO

Keywords:
Metal alloy profiles/sections
Bending
Curvature
Extrusion
Analytical analysis
Upper-bond method

ABSTRACT

An analytical upper-bound-based model for predicting curvature of bent metal alloy profiles obtained through a novel extrusion process, differential velocity sideways extrusion (DVSE), previously proposed by the authors, has been first-time developed. Finite element modelling and simulation and model material experiments, which were validated by extrusion of AA1050, have been performed to determine the geometry of the deformation zone and assess the accuracy of the analytical model. The extrusion force, curvature, and effective strain predicted by the analytical method agreed well with results from experiments and FE simulation. It was shown that the punch with a lower velocity experiences a lower extrusion force, which increases both with increase of its velocity and the extrusion ratio. The extrusion force on the faster punch with a constant velocity v_1 changes quite slightly with the increase of the velocity v_2 of the slower punch. Various values of curvature, which decrease with the increase of the punch velocity ratio v_2/v_1 and the decrease of the extrusion ratio, can be achieved through the DVSE process. DVSE is a novel process which leads to larger effective strain per pass than that in the equal channel angular extrusion (ECAE).

1. Introduction

Reducing the weight of metal components used in land, sea and air conveyances leads to reducing fuel consumption and therefore decreasing CO_2 emissions. Aluminium alloy profiles with various cross-sections are extensively used as construction elements in industrial manufacturing for the production of ultra-light structures, on account of their good combination of light weight and high strength. This is also because they can achieve the construction of complex, often aerodynamically shaped structures with little or no welding and cutting required, thus enhancing productivity [1–4]. Taking into account the demand for reduced aerodynamic resistance as well as improved aesthetics, the availability of precisely shaped curved aluminium alloy profiles with high performance properties is very attractive.

Conventional curved profile forming methods normally start with the manufacture of semi-finished straight profiles, by shape rolling or extrusion, followed by subsequent bending procedures such as; stretch bending, rotary draw bending, press bending, or roll bending (three-, four-, and six-roll processes). However, these production methods have the disadvantage of being two stages and also incurring springback and cross-sectional distortion in the second stage bending operation [5–10]. Recently, several novel integrated extrusion-bending methods have been proposed. The first one is curved profile extrusion (CPE) developed by Kleiner et al. [11,12] in which the hot metal billets are directly formed into continuous profiles/sections and bent simultaneously, thus greatly improving productivity. This process is based on the conventional straight extrusion process, with bending apparatus installed directly after the die exit to deflect the extruded profile to the prescribed curvature. Muller et al. [13,14] proposed a method in which a segmented regulating guiding device composed of serially placed bending discs is positioned at the die exit to bend the extruded straight profile. Since curvature is generated at the die exit where the material is still in the fully plastic state, this forming process produces profiles/sections with no springback, reduced residual stresses, and minimal cross-sectional distortion. Another way of achieving extrusion-bending integration is by utilising an inclined die, through which the material flow velocity distribution along the profile cross-section in the deformation zone can be adjusted. Shiraishi et al. [15–17] proposed a novel integrated extrusion-bending forming method for producing curved profiles, in which a billet is extruded through a die aperture inclined towards the central axis of the container at a predetermined angle. Experiments were carried out using plasticine as billets and it was found that by adjusting the inclination angle of the die aperture, the curvature of the extruded profile can be varied, and greater inclination angle leads to increased curvature.

* Corresponding author.
E-mail address: jianguo.lin@imperial.ac.uk (J. Lin).

https://doi.org/10.1016/j.ijmecsci.2018.02.028
Received 15 October 2017; Received in revised form 10 February 2018; Accepted 12 February 2018
Available online 13 February 2018

Nomenclature

D_1	diameter of the billet
D_2	diameter of the extruded profile
dV	differential volume element of the plastic deformation zone (PDZ)
h	height of the dead metal zone (DMZ)
k_0, k_f	initial and final shear yield stresses of the material
$\bar{k}$	mean shear yield stress of the material
m	constant friction factor
F_1, F_2	extrusion forces of the upper and lower punches
F_{1u}, F_{2u}	upper bound of extrusion forces of the upper and lower punches
R_c	bending radius of the profile
S_0	cross-sectional area of the billet
S_3, S_4	cross-sectional areas of the related profile
S_f, S_v	areas of frictional and velocity discontinuity surfaces
Δv	amount of velocity discontinuity
v_1, v_2	extrusion velocities of the upper and lower punches
v_{1e}, v_{2e}	maximum and minimum material flow velocities across the die exit orifice
v_3, v_4	velocities at the volume (mass) centre of the related profile
$\dot{W}_e$, $\dot{W}_i$	external and internal power supplies
$\dot{W}_{S_f}$, $\dot{W}_{S_v}$	power dissipated on the frictional and velocity discontinuity surfaces
$\bar{y}_3$, $\bar{y}_4$	coordinates of the volume (mass) centre of the related profile

Greek symbols

α, β, θ, φ	angles in the hodograph
γ	engineering shear strain
$\dot{\varepsilon}_{ij}$	strain rate tensor
κ	bending curvature of the extruded profile
λ	extrusion ratio
ξ	eccentricity ratio

The authors have proposed a new extrusion-bending process, differential velocity sideways extrusion (DVSE) [18,19]. The basic principle of this method is that profiles are bent in an extrusion die orifice due to a velocity gradient across the cross-section of the extrudate. The velocity gradient is achieved by controlling the velocities of punches at each end of the billet work-piece. It has been shown that curvature of extrudate is dependent on the ratio of velocities of the two extrusion punches and the extrusion ratio. For a particular extrusion ratio, velocity ratio can be chosen to produce a particular curvature. An analytical model for predicting curvature of extrudate needs to be established for a deeper understanding and wider application of the DVSE forming method. The upper bound method has been extensively used to predict the forming force, optimise the forming process, analyse the deformation characteristic of the material in the extrusion of profiles, ring rolling and forging processes, and to determine and minimise the exit profile curvature in the extrusion process of non-symmetrical profiles [20–25], etc. It is considered to be suitable for analysing the complicated deformation characteristics of the DVSE process and to estimate the distribution of the profile curvature, both of which are influenced by several process parameters.

In this paper, an analytical model, based on the upper bound method, for estimating the distribution of extrusion force, curvature and effective strain of the extruded profile formed by DVSE, is developed. Finite element and physical models from practical experiments, have been used to assess the validity of the analytical model. The effects of punch velocity ratio, and extrusion ratio on extrusion force, curvature and effective strain of the formed profile, have been analysed in detail. The findings provide understanding needed for industrial exploitation of the DVSE process.

2. Theoretical model

2.1. Upper bound model

The upper bound model is formulated for a material extruded through circular orifices using the DVSE process. As shown as a section in Fig. 1a, consider a cylindrical container in which a billet, forced by a punch at each end, is extruded sideways through a circular die. The corresponding punch velocities and extrusion forces are v_1, F_1 and v_2, F_2, respectively. The initial diameters of the billet and the container bore are both D_1, the diameters of extruded profile and die exit orifice are both D_2. For a rigid-plastic material, amongst all kinematically admissible velocity fields, the actual one minimizes the internal power required for material deformation:

$$\dot{W}_i = \int_V \sigma_{ij}\dot{\varepsilon}_{ij} dV + \int_{S_v} k\ \Delta v\ dS_v + \int_{S_f} mk\ \Delta v\ dS_f - \int_{S_t} P_i v_i\ dS \qquad (1)$$

where k is the current shear yield stress of the material, m is the constant friction factor, σ_{ij} and $\dot{\varepsilon}_{ij}$ are the stress and strain rate tensors respectively, V is the volume of the plastic deformation zone, S_v and S_f are the areas of velocity discontinuity and frictional surfaces respectively, S_t is the area where tension may occur, Δv is the amount of velocity discontinuity on the frictional and discontinuity surfaces, v_i and P_i are the velocity and traction applied on S_t, respectively.

Fig. 1b shows a two dimensional deformation model considered on diametral planes of container and die. Based on the experimental and modelling results (see Section 4.1), the dead metal zone (DMZ) can be reasonably regarded as a triangle ΔAFC in this plane (the boundaries of the DMZ are simplified from the arc curves to straight lines, as the height BF of the dead zone is relatively small) whose central extension line BG divides the plastic deformation zone (PDZ) and the exit die channel into two parts; namely AB of length ξD_2 and CB of length $(1-\xi)D_2$, respectively. Here the variable $\xi = g(v_2/v_1, \lambda)$ represents the effect of v_2/v_1 on the PDZ and DMZ for a given extrusion ratio λ. The material flowing into these two parts comes from both upper and lower regions of the container. The area of the DMZ and the position of line BG vary with values of v_2/v_1 and λ. When $v_2/v_1 = 1$, line BG is in the centre of the die exit channel. As v_2/v_1 decreases, it moves towards the side which has a lower extrusion velocity (v_2). As shown in Fig. 1b, the volume considered for analysis is divided into five regions. Regions I–IV are the PDZ in which the material undergoes plastic deformation, region V is the DMZ. A simple shear model is used here, thus the PDZ is considered as consisting of several single shear planes [26,27]. That is, the modes of deformation are composed of rigid blocks of material separated by the velocity discontinuity planes *AE, EF, AF, CD, DF* and *CF*.

Upper-bound solutions are obtained utilizing hodographs involving velocity discontinuities which are linear and occur only in the tangential direction along velocity discontinuity planes [26,27]. Fig. 1c shows a solution utilizing a kinematically admissible hodograph. Before entering regions I and II, the material moves as a rigid body with the velocities v_1 and v_2 in the direction MO_1 and PO_2 until encountering the velocity discontinuities Δv_{AE} and Δv_{CD} at surfaces AE and CD, and are constrained to move in directions MN and PQ with velocities υ_{I} and υ_{II} respectively, at oblique angles β and θ to the die exit. Then υ_{I} and υ_{II} further encounter velocity discontinuities Δv_{EF} and Δv_{DF} at surfaces EF and DF, and are forced to enter regions III and IV with velocities v_3 and v_4 in the hypothetical horizontal direction. It should be noted that v_3 and v_4 are the mean velocities of regions III and IV, since there is no velocity discontinuity between regions III and IV, and the velocity for the material flowing out of the die exit should be gradient where the upper side has the maximum velocity v_{1e}, the lower side has the minimum velocity v_{2e} and the boundary FG has the continuous velocity v_m. The die exit channel of the DVSE is sufficiently short [19] to ensure the