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Local sheet thickening by in-plane swaging

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ABSTRACT

This paper presents a new sheet-bulk forming process to locally pile-up material in thin sheets for subsequent forming or joining operations. An analytical solution is proposed for explaining the influence of the major process parameters, estimating the thickening of the pile-up material and determining the normal and thrust forces applied by the tools. The approach is built upon the slip-line field theory under plane strain assumptions and results are compared against finite element predictions and experimental results using Aluminium EN AW-1050A (EN 573-3) sheets with 3 mm thickness. The last part of the paper introduces a modified tool geometry that is able to control the pile-up material for subsequent mechanical fastening operations.

1. Introduction

The identification of sheet-bulk metal forming (SBMF) as a new manufacturing technology in which conventional sheet and bulk metal forming processes are combined to plastically deform sheets and plates with intended three dimensional material flow is attributed to Merklein et al. [1]. SBMF is aimed at replacing commonly used multi-stage stamping, fine blanking and precision machining operations for the production of net shape (or near-net shape) components having a high ratio of surface area to thickness and local functional features such as teeth, ribs and solid bosses positioned outside the plane of the sheets or plates from which they are produced. Pulleys, vibration dumpers and transmission gears of automotive are among the target components of this new forming technology.

Earlier developments of special purpose processes to fabricate sheet metal components with different thicknesses are due to Greisert et al. [2], who introduced flexible rolling to produce sheets with periodically varying thickness and to Merklein et. al. [3], who proposed the utilization of tailored blanks for producing functional elements with different thicknesses. In fact, these two developments are among the first solutions towards lightweight and load-adapted design of sheet metal components with functional features positioned outside the initial surface of the sheets but they are not flexible enough for producing components that require local thickening instead of periodically or tailored varying sheet thickness.

From the above said, it is concluded that a major objective in SBMF is the development of simple and effective forming procedures to obtain local thickening of sheets and plates with dimensions up or above their original thicknesses (Fig. 1). The first steps towards this objective were taken by Sieczkarek et al. [4] who presented a novel five-axis press concept that is capable of performing different forming sequences such as embossing, rolling and compression. This work was followed by an investigation on the deformation mechanics of sheet-bulk indentation and by presentation of a closed-form analytical solution to estimate the pressure and force applied by a flat indentation punch in the direction perpendicular to the sheet thickness [5].

The present paper extends previous work on local thickening of sheets by considering in-plane swaging (also designated as ‘local boss forming’) with a cylindrical roll. The main idea is to locally pile-up material in a sheet (Fig. 1a) for subsequent forming or joining of functional elements. The process can also be applied to localized thickening of cup walls and tubes (Fig. 1b).

The paper has three major broad objectives besides that of proposing a new sheet-bulk metal forming process. Firstly, it proposes an analytical model build upon the slip-line field theory to explain the influence of the major process parameters, to estimate the thickening of the pile-up material and to calculate the normal and thrust forces applied by the roll. Secondly, it aims to identify the process window and to quantify the deviations of the actual material flow from the plane strain deformation conditions that are assumed by the analytical model. And, thirdly, it proposes a modified tool design to control the geometry and volume of the pile-up material. The proposed modification in conjunction with micro-hardness measurements is very important to determine the overall workability of the piled-up material for subsequent localized forming or joining operations.

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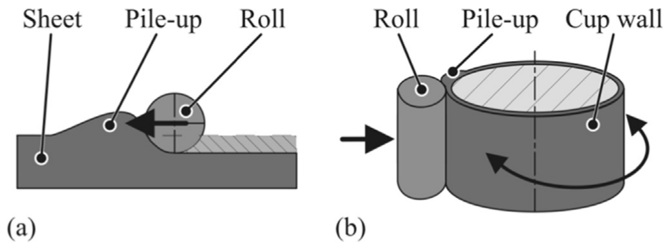

Fig. 1. Local thickening of (a) a sheet (or plate) and of (b) a cup wall (or tube) by in-plane swaging with a cylindrical roll.

2. Analytical model

Fig. 2 presents the pile-up of material by combination of indentation and in-plane swaging of a sheet with a cylindrical punch. The basic components of the process are; (i) the sheet blank, (ii) the cylindrical roll and (iii) the fixture system that clamps the sheet blank to the machine worktable.

The analytical model to be developed is focused on the in-plane swaging that follows the initial indentation stage. From a deformation mechanics point of view, during in-plane swaging the roll moves perpendicular to sheet thickness and plastic flow is three-dimensional due to the increase in width w of the pile-up material (hereafter designated as 'pile-up spread'). However, in the proposed analytical model it is assumed that the pile-up spread $s = (w_1 - w)/w \approx 0$, where w_1 is the final width of the pile-up material and w is the width of the roll. This allows analysing plastic flow under plane strain deformation conditions and to develop an analytical solution based in the slip-line field theory for steady-state deformation conditions. The analysis of the transient plastic flow associated to the early deformation stages will not be addressed, although an analytical model for the initial indentation stage could easily be setup from previous work on indentation by means of frictionless cylindrical punches carried out by Hill [6] in 1948.

Under these conditions, the main process parameters that will be included in the proposed analytical model are; (i) the sheet thickness t, (ii) the radius R of the roll, (iii) the width w of the roll and (iii) the indentation depth i. The mechanical behaviour of the material is left out of the process parameters because the slip-line field theory requires material to be rigid-ideally plastic (i.e. no strain hardening effects are taken into account).

The two other assumptions derived from the application of slip-line theory are; (i) the material is isotropic and homogeneous, and (ii) the effects of temperature and strain rate are ignored. In addition to this, authors also assumed the coefficient of friction μ (defined as the ratio of shear and normal stresses) to vary along the contact interface between the sheet and the roll.

Fig. 3a–c, shows the proposed slip-line fields for the initial (Fig. 3a), transient beginning (Fig. 3b) and the transition to steady-state in-plane swaging (Fig. 3c). As seen in the figures, the shape of the slip-line field changes as deformation continuous up to the instant of time when the pile-up material detaches from the surface of the roll and steady-state plastic deformation conditions are attained (Fig. 3c).

All the three slip-line fields make use of a centred-fan with equal radius, but while in Fig. 3a the origin of the centred-fan is a singularity point O located on the surface of the roll, in case of Fig. 3b and c the origin of the centred-fan $P_{1,I}OP_{3,I}$ is located outside the plastic deformation region. As a result of this, the slip-line field consists of an extended centred-fan with α (clockwise maximum shear lines) and β (anticlockwise maximum shear lines) meeting orthogonally at the roll surface but with different inclination angles γ to the roll surface. In fact, the proposed solution assumes γ to decrease from $\pi/4$ (frictionless condition) at $P_{1,II}$ to $\psi - \pi/4$ at $P_{3,I}$, where ψ represents the contact angle for the pile-up material detaching from the roll.

The decrease in γ replicates the increase in the friction coefficient μ that is expected to occur along the contact interface between the sheet and the roll when we move from point $P_{1,II}$ where the pile-up material detaches from the roll to point $P_{3,I}$ where the roll is tangent to the plastically deformed surface of the sheet.

The remaining fields are made of straight lines of constant average stress (for example, $P_{0,I}P_{1,I}P_{1,II}$ in Fig. 3b and c). The dashed line limiting the straight lines of constant average stress in the leftmost region of Fig. 3b and c represent a discontinuity in stress between the rigid material and the plastically deforming regions. In connection to the volume elements included in Fig. 3c it is worth noting that $\sigma_Y = 2k$, where σ_Y is the flow stress and k is the shear yield stress according to Tresca's yield criterion.

Now, by focusing on the slip-line field corresponding to steady-state plastic deformation conditions and taking into account the angular relationships that are given in Fig. 3d it is possible to write the radius R_{sl} of the extended centred-fan with a centre in point O as a function of the radius R of the roll as follows,

$$R_{sl} = \frac{1}{2}\left(\frac{R\sin\psi}{\cos\left(\frac{3}{4}\pi - \psi\right)} + \frac{R - R\cos\psi}{\sin\left(\frac{3}{4}\pi - \psi\right)} \right) \tag{1}$$

The enlarged detail of Fig. 3d gives the thickness t_p of the pile-up material as a function of the radius R of the roll and of the indentation depth i,

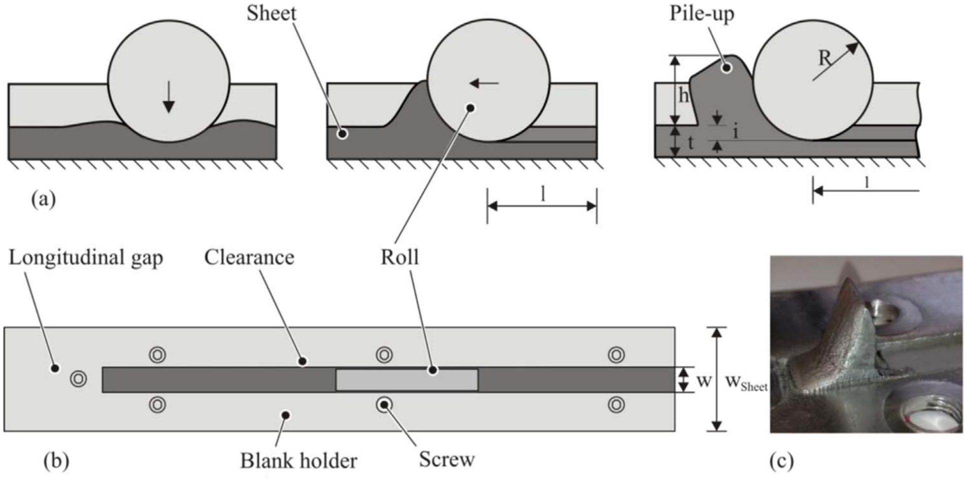

Fig. 2. Local thickening of sheet by in-plane swaging. (a) Schematic evolution of the pile-up material from the initial indentation stage up to steady-state plastic deformation conditions; (b) Top schematic view of the experimental setup; (c) Photograph showing the pile-up material in an experiment performed with aluminium EN AW-1050A.