



# Thickening of cup sidewall through sheet-bulk forming with controllable deformation zone



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## ABSTRACT

Buckling is one of the main challenges in thickening the sidewall of a deep drawn cup. To overcome this problem, a novel sheet-bulk forming method, upsetting with a controllable deformation zone, was developed in this study to prevent the buckling during sidewall thickening. In this method, the material from the protective cavity of the die is pushed into the forming cavity under a counter force to establish a stabilised deformation zone, which can eliminate the limitation of the initial slenderness ratio in conventional upsetting methods. The experimental and simulated results reveal that the occurrence of buckling can be successfully avoided through upsetting with a controllable deformation zone. The forming load tends to remain unchanged because of the existence of a stable deformation zone. Additionally, the forming quality can be improved, and a uniform distribution of hardness in the cross section can be obtained, thereby improving the performance-in-service.

## 1. Introduction

Increasingly complex parts, such as gear drums and synchroniser rings, with functional integration and optimal wall thickness are being designed to fulfil the requirement of lightweight parts in the automotive industry, consequently saving energy and reducing emissions. The manufacturing process of these parts should possess high geometrical accuracy, adequate mechanical properties, and cost efficiency (Kleiner et al., 2003). Therefore, a new forming process, called sheet-bulk metal forming (SBMF), is intended to manufacture three-dimensional sheet parts by controlling the material flow. In Japan, a same process, plate forging, has been introduced and was summarised by Mori and Nakano (2016).

SBMF was first proposed and popularised by Merklein et al. (2010), and considerable fundamental research work was performed within the Transregional Collaborative Research Centres 73 as introduced in Merklein and Hagenah (2016). An overview of the investigation in this field was presented by Merklein et al. (2012a), in which the material flow, tooling, and resulting product properties were highlighted. And as reported by Merklein et al. (2011), there exist complex interactions between the forming zones of high and low strains in SBF. Deformation in the sheet thickness direction causes thinning or thickening of the blank, which is used to form parts with an optimised cross section (Mori, 2012). Large forming load is a problem because of the expansion

of the contact surface. Thus, new methods were proposed for various applications. Abe et al. (2014) proposed a multistage stamping process to thicken the corner area. In the first two stages, much more material was gathered at the bottom of the cup by a conical punch, and then the corner was thickened by flattening the conical bottom with a flange. Schneider and Merklein (2013) combined deep drawing and upsetting in a single stage to thicken the sidewall to achieve a geared shape. However, this process has some limitations in upsetting, because folding or grooving can occur. To overcome this problem, a blank tailored by flexible rolling and orbital forming was applied (Merklein et al., 2012b). In Behrens et al. (2015), the forging laps were avoided by adding a lock bead in the die cavity. Alves et al. (2017a) introduced sheet-bulk forming to overcome the challenges of annular flanges forming in thin-walled tubes. A new boss-forming process was proposed to pile up the material along the axial direction through partial compression of the tube wall to obtain the localised annular thickening. Furthermore, a die cavity was used, and kinematics were changed to allow the upper and lower dies to move together, which effectively eliminated the direct dependency between the height and radius of the annular flanges that is typical to boss forming (Alves et al., 2017b). A triple cup with different wall thicknesses was manufactured using a two-stage method proposed by Wang and Yoshikawa (2014). The bottom was thickened under complete constraint of the die at the first stage, and then two top dies were moved downward at the second stage

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to extrude the material into the upper and lower hollow bosses.

Moreover, upsetting in the longitudinal direction is another popular thickening method to obtain optimum distribution of thickness. However, buckling under compression stress remains a major challenge. To overcome this problem, Wang et al. (2011) proposed a process combining deep drawing, reverse drawing, and piercing to form a double-layer cup with different wall thicknesses. The thickness of the inner sidewall was increased from 2 to 4 mm without buckling. The key idea was to reduce the gap between the sidewall and inner surface of the die by increasing the number of forming stages. Katoh et al. (2002) provided a new thickening method by upsetting under the constraint of an inclined die container instead of performing the upsetting directly in the perpendicular direction. Using the inclined die container avoided buckling to some extent. However, the shape of the sidewall was limited as well. To prevent buckling, a multimotion press was adopted by Suzumura et al. (2002). The bottom base of the cup was drawn by the inner punch, and the sidewall of the cup was pushed and thickened by the outer punch. Under the constraint of the outer die, no buckling occurred during the process. A similar idea was proposed by Wang et al. (2016) to form a cup-shaped preform with various thicknesses by combining upsetting, deep drawing, and burring, and gear teeth were formed on the sidewall through extrusion and subsequent axial sizing.

Because of the challenges of buckling and manufacture efficiency for sidewall thickening, this study proposed and investigated a one-stage upsetting operation along the longitudinal direction of the sheet assisted by a counter punch under constant back pressure. Buckling was successfully prevented by employing a controllable deformation zone, and the quality was more uniform than that of conventional upsetting. Through experiments and numerical simulations, the mechanism of this new sheet-bulk forming process was analysed and the influence of counter force were investigated, which is the most important parameter that determined the forming results. The structure of the paper is organized as follows. Section 2 presents the sheet-bulk forming method with a controllable deformation zone. Section 3 presents the related experiments and corresponding numerical modelling issues. The comparison of results and discussions related to the mechanism of the controllable deformation zone and the hardness distribution are presented in Section 4. Finally, the conclusions are summarised in Section 5.

## 2. Sheet-bulk forming with controllable deformation zone

### 2.1. New solution for thickening the sidewall of the cup

A new solution for thickening the sidewall of the cup, sheet-bulk forming with a controllable deformation zone, is shown in Fig. 1, which includes the tool concept and geometrical shapes of the workpiece before and after forming. Punch, die, mandrel, and counter punch are the four core tools required in this method. The die has two cavities. The upper cavity is the forming cavity, and the lower cavity is the protective cavity.

Initially, the pre-drawn cup is placed into the tool and surrounded by the punch, die, mandrel, and counter punch. The top surface of the sidewall aligns with the dividing surface of the two die cavities. The mandrel and counter punch are imposed with counter forces  $F_m$  and  $F_c$ , respectively. Thereafter, the punch moves upward at a speed  $V_p$ . Because the die is fixed, the mandrel and counter punch are pushed up with the increasing internal force of the workpiece. To prevent the sidewall material from flowing into the bottom area of the cup, an appropriate counter force,  $F_m$ , is crucial. The upward counter punch releases the forming cavity of the die step by step, which attracts the material flowing into the spared area to thicken the sidewall gradually. When the top surface of the punch aligns with the dividing surface of the die cavities, the thickening of the sidewall is completed.

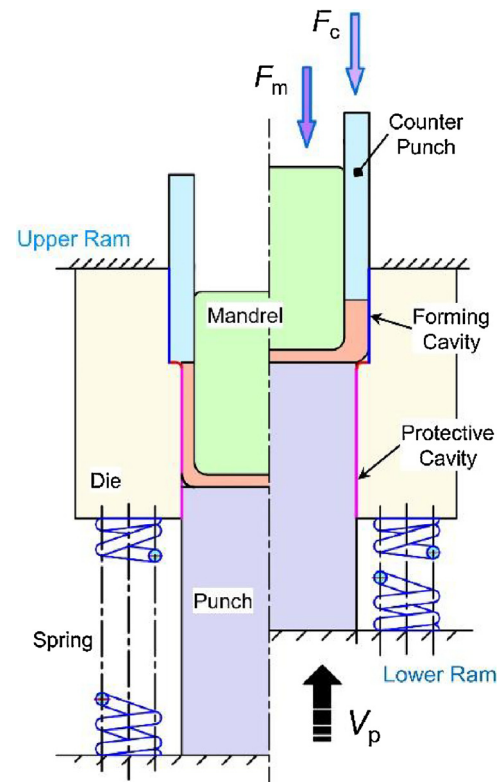


Fig. 1. Sheet-bulk forming of cup sidewall with controllable deformation zone.

### 2.2. Feature simplification

As mentioned previously, the material of the sidewall is likely to flow into the bottom area of the cup, which deteriorates the quality of the sidewall. To investigate the core principle of buckling prevention and discuss the direct influence of counter force  $F_c$ , feature simplification was performed, and the corresponding tool was designed as shown in Fig. 2.

Fig. 2a presents a schematic tool design of upsetting with a controllable deformation zone (U-CDZ), in which a cup without a base is used as an initial workpiece. The principle of sidewall thickening is identical to that shown in Fig. 1. Because of the removal of the base, the punch integrates the function of the mandrel, which plays a role not only in pushing the workpiece into the forming cavity but also in fixing the inner surface of sidewall. The counter force,  $F_c$ , is the key parameter and determines the forming cavity, which determines the forming quality.

The conventional method of upsetting perpendicular to the thickness direction is shown in Fig. 2b. In this case, the die has only one cavity, the diameter of which is equal to the outer diameter of the final workpiece. The counter punch is maintained unchanged. When the punch moves upward, the sidewall is thickened simultaneously. The slenderness ratio  $l_0/t_0$  and the thickness increment  $t_{gap}$  are the most important parameters.

## 3. Experiment and simulation

### 3.1. Material

To reduce the influence of the anisotropy, pre-deformation as well as the uneven sidewall thickness of the deep drawn cup on the final forming results, a machined cup of aluminium alloy AA6063-T6 was used as experiment billet. To focus on the thickening quality of the sidewall, the base of the cup was removed.

Compression test under room temperature was performed to obtain

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