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Full Length Research Paper

Prediction of geometric defects in the cold embossing of AA6061 aluminum alloy by finite element analysis

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The precision of near-net shape manufacturing processes such as cold forging is crucial. Defects may affect the assembly accuracy and thus cause decreased system performance. Therefore, these defects must be predicted and minimized as early as possible before proceeding to the manufacturing stage. This paper aims to study the geometric defects in the cold embossing pin head. The defects can be measured based on the incomplete filling and geometries of bulging. The effect of the distance to edge (DTE) on the defect pattern is predicted based on the material flow pattern. The DTE is found to have a significant effect on defect formation. The size of bulging is reduced and the filling ability is improved with increased DTE.

Key words: Cold embossing, material flow pattern, geometrical defect, distance to edge.

INTRODUCTION

The main goal of near-net shape manufacturing is to produce parts that are much closer to the finished size, shape, and tolerance. Defects affect not only the quality of parts, but also the assembly accuracy (Volertsen, 2000). Hence, defects may influence the system performance (Zamponi et al., 2009). One of the main concerns of net-shape manufacturing is to avoid or at least minimize secondary processes such as machining, which can reduce the cost of production (Kopac and Sokovic, 1999). Therefore, defects need to be predicted and prevented as early as possible.

Cold forging is a net-shape manufacturing process that has recently received much attention. This process depends on many factors, including friction, part geometry, die shape, as well as die and workpiece temperatures (Arentoft and Wanheim, 1997). The difficulty in controlling all these factors tends to cause defects. Arentoft and Wanheim (1997) have classified forging part defects into six types: fold, shear defect, surface defect, form defect, crack, and structural defect. The causes of defects include die deflection, yielding or wear, and eccentricity or buckling due to flow imperfection.

During incremental forming, Hussain et al. (2007) have observed three types of forming defects, namely, squeezing out of metallic wall, corner fold and bulge height. These types can be differentiated based on their formation, location, and appearance. Park and Hwang (2007) have optimized the performance design to avoid under-filling and folding. Tahir (2007) has discussed die filling and barrel formation during the lateral extrusion process. Narayanasamy et al. (2006) have studied the barreling defects of various metals during the cold upsetting process. Similarly, Baskaran and Narayanasamy (2006) have applied white grease as a lubricant to determine defect dimensions such as height, contact diameter, and bulge diameter at different stress

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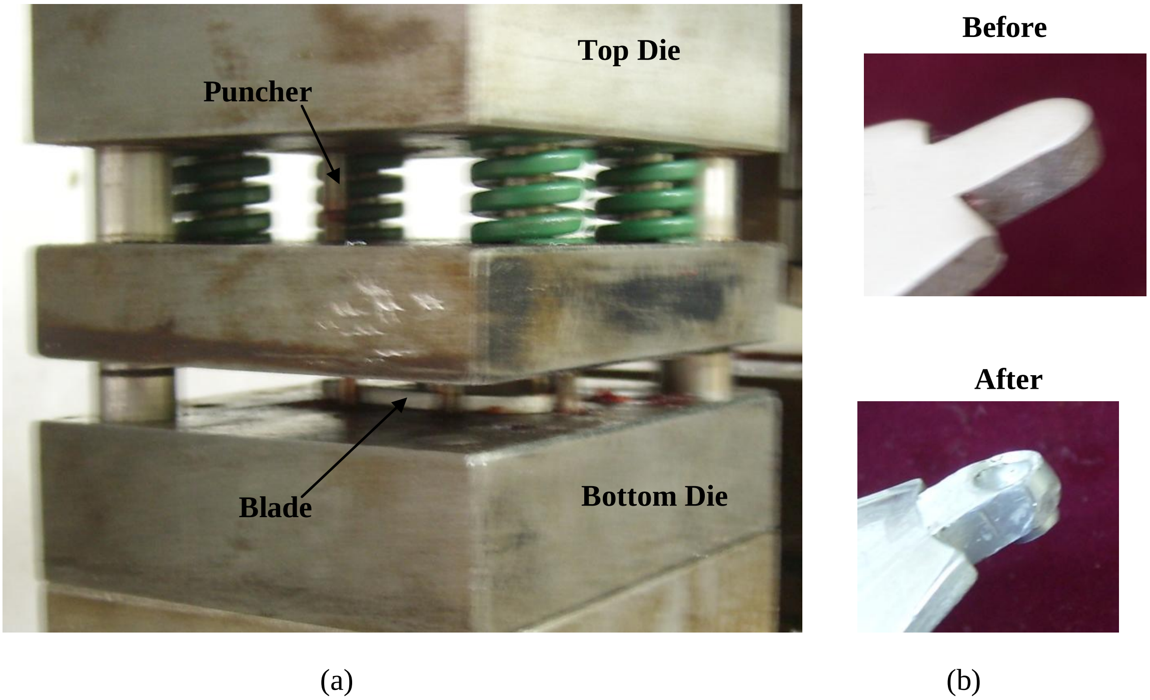

Figure 1. (a) The embossing tooling and (b) blade before and after the pin heading.

ratio parameters. Yilmaz et al. (2004) have experimented on conventional closed-die forging to study the effects of aspect ratios and indentation on the forging load and die filling. Defects related to metal flow imperfections are a research hotspot. Recently, Chan et al. (2009) have proposed a dynamic change in the tooling geometry to control the most common flow-induced defects, such as folding. Kang and Bae (2008) have studied the effect of the die shape ratio to forging part defects based on the metal flow. Lin and Lin (2003) have investigated the folding defects that occur in barreling formation during cylinder upsetting with a hollow die using DEFORM-2D. They have found two locations where fold defects may occur, i.e., around the equatorial plane of the workpiece and at the intersection zone of the barrels. On the other hand, Hirota (2001) has simulated the two-dimensional (2D) micro-extrusion process and found that defects can be predicted, even for micro-scale forging, based on the material flow pattern.

In general, embossing refers to a metalworking operation used to create raised surfaces or lettering, usually on sheet metal, without changes in thickness (Namoco et al., 2007). In most cases, embossing is carried out symmetrically. Therefore, in the cold embossing of polymer materials, the only problem is swallowtailing, as presented by Rowlad and King (2004). However, studies on asymmetrical embossing are very limited.

This paper aimed to investigate the effect of punch geometry and location of the pin head on defect formation to ensure the accurate assembly of the blade to the hubs. An overview of the embossing process of an aluminum pin head is provided, followed by the methodology. The results are discussed and the paper ends with conclusions.

OVERVIEW OF THE PIN HEAD EMBOSSING PROCESS

The pin head is a special feature designed to ensure the accurate assembly of the blade to the hubs. Figure 1(a) shows the tooling of the embossing process. Figure 1(b) illustrates the workpiece before and after embossing. The pin head must be formed precisely to avoid unwanted blade movement that may affect the propeller performance. One of the main parameters that affect the propeller performance is the twist angle, which depends on the geometric precision of the blade and its assembly accuracy (Abu-Bakar et al., 2009).

METHODOLOGY

The main objective of this study was to investigate the effects of the distance to edge (DTE) to the geometric defects of the embossed pin head. The final assembly of the propeller is shown in Figure 2. Several geometries need to be taken into account because the accuracy of each parameter affects the assembly of the part itself. The DTE is one such design parameter. Given that the geometry of the pin head diameter depends on the die cavity, the size of the head is not critical. In this design, the DTE should be less than 1.0 mm (DTE ≤ 1.0) because at higher values either define initially or

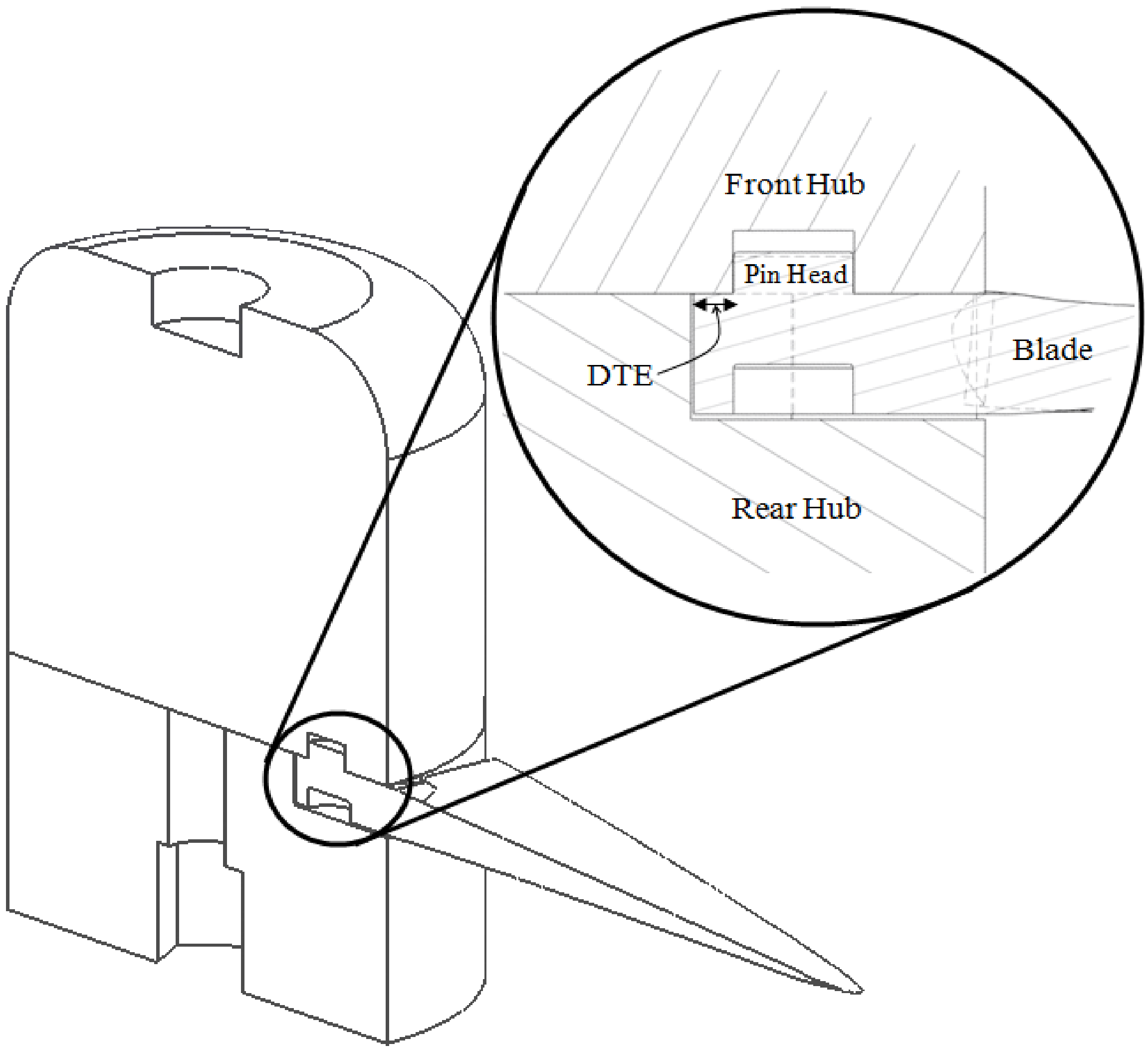

Figure 2. Final assembly of the AUV propeller.

due to defect, it will cause overlapping or difficulty during assembly.

Modeling

Theoretically, for the upsetting of bulk formation, the governing equations for the solution of the mechanics in plastic deformation for rigid-plastic and rigid-viscoplastic materials involve equilibrium equations, yield criteria, constitutive equations, and compatibility conditions. These elements can be presented by considering the construction of the following functional (Kobayashi et al., 1989):

$$\prod = \int \bar{\sigma}\dot{\bar{\varepsilon}}dV - \int_{sp} t_i v_i dS \qquad (1)$$

Where $\bar{\sigma}$ is the effective stress, $\dot{\bar{\varepsilon}}$ is the effective strain rate, F_i is the surface tractions, and u_i is the velocity components.

The incompressibility constraint on the admissible velocity fields in Equation (1) may be removed using the penalized form of the incompressibility, as given by:

$$\delta\prod = \int_v \bar{\sigma}\delta\dot{\bar{\varepsilon}}\, dV - \int_{S_F} t_i \delta v_i\, dS + K\int_v \varepsilon\dot{v}\delta\, dV = 0 \qquad (2)$$

Where $\dot{\varepsilon}_v = \dot{\varepsilon}_{ii}$ is the volumetric strain rate and k is the penalty constant, a very large positive number. Eqs. (1) or (2) is the basic equation for the finite element formulation.

The 2D model of the simulation is shown in Figure 3. The model consists of a preform/workpiece as well as punch, top and bottom dies. Both dies were considered as a rigid body. The preform was placed between the dies before the embossing process. In this process, the workpiece was pressed by a punch at constant speed of 250 mm/s. The initial thickness of the AA6061 workpiece was 3.0 mm. The punch geometries were as follows: diameter, 3 mm; DTE, 0.7 mm; and depth or total stroke, 2.0 mm. No lubricant was used and the material to be formed was aluminum; thus, the friction coefficient was assumed to be 0.4 and the initial temperature of the workpiece, punch, and die was 25 °C (room temperature). For this study, the rigid-plastic finite element (FE) method was applied in the analysis of the deformation that involved 3000 elements for the

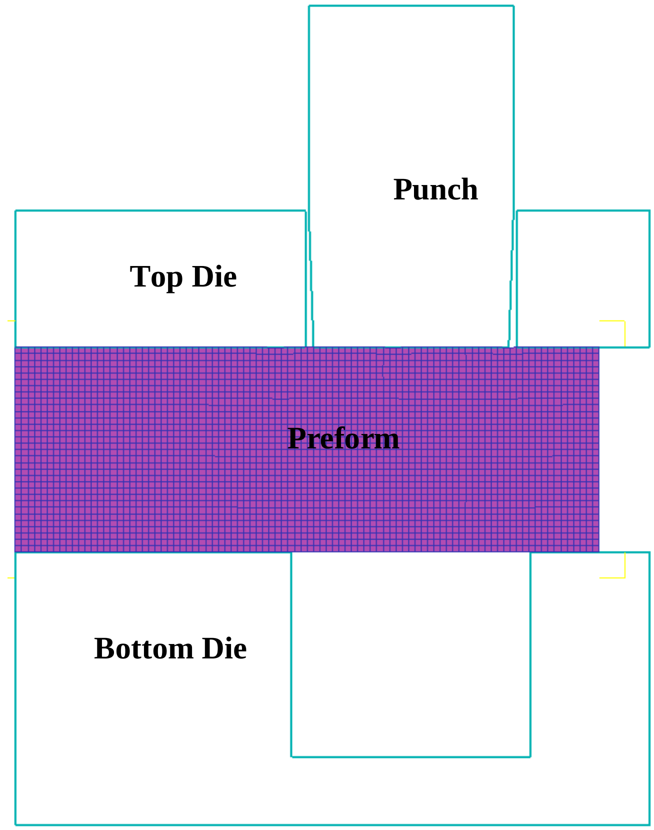

Figure 3. The FE model of the embossing process at initial position.

Table 1. Material properties of workpiece.

Parameter	Workpiece
Material type	AISI 6061
Modulus Young (GPa)	68
Yield Strength (MPa)	386
Poisson ratio	0.35
Hardness	HRC-24

preform. The material properties are listed in Table 1. The material for the punch and die is D2 tool steel.

Two major defects were considered, i.e., the unfilled region and bulging. The unfilled region is quantified based on the filling ratio *AR*, which can be described as the ratio of the filled region to the fully-filled part:

$$AR = \frac{\text{Filled Region}}{\text{Fully-Filled Region}}.$$

A lower ratio means more unfilled regions that depict the larger defect. To ensure consistency of the results, a programme was developed using Matlab. The image of the embossed pin head was captured from the FE simulation, from which the geometry of the part was determined. Subsequently, the filling region can be estimated. Figure 4 shows the image of the forged pin head obtained from the FE results. In the current work, two features are considered, the height and width of the embossed pin head for the bulging evaluation.

RESULTS AND DISCUSSION

This study focuses on the flow of the material on the right section of the pin head. The initial gemoteries are punch diameter of 3 mm and depth of 2 mm. The simulation result reveals that the cavity can only be spotted when the stroke is 1.0 mm. When the punch stroke is 2.0 mm, the material tends to flow outward and bulging occurs, as shown in Figure 5.

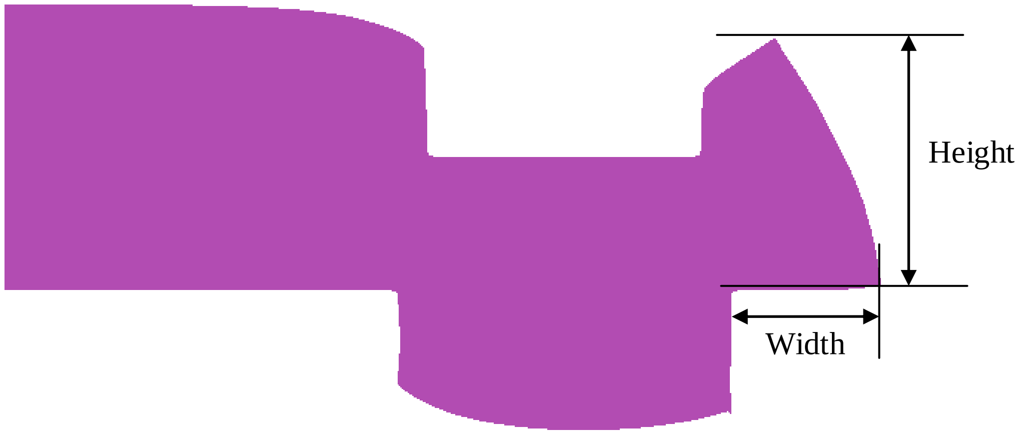

Figure 4. The resulted embossed pin head and the bulging geometries to be measured.

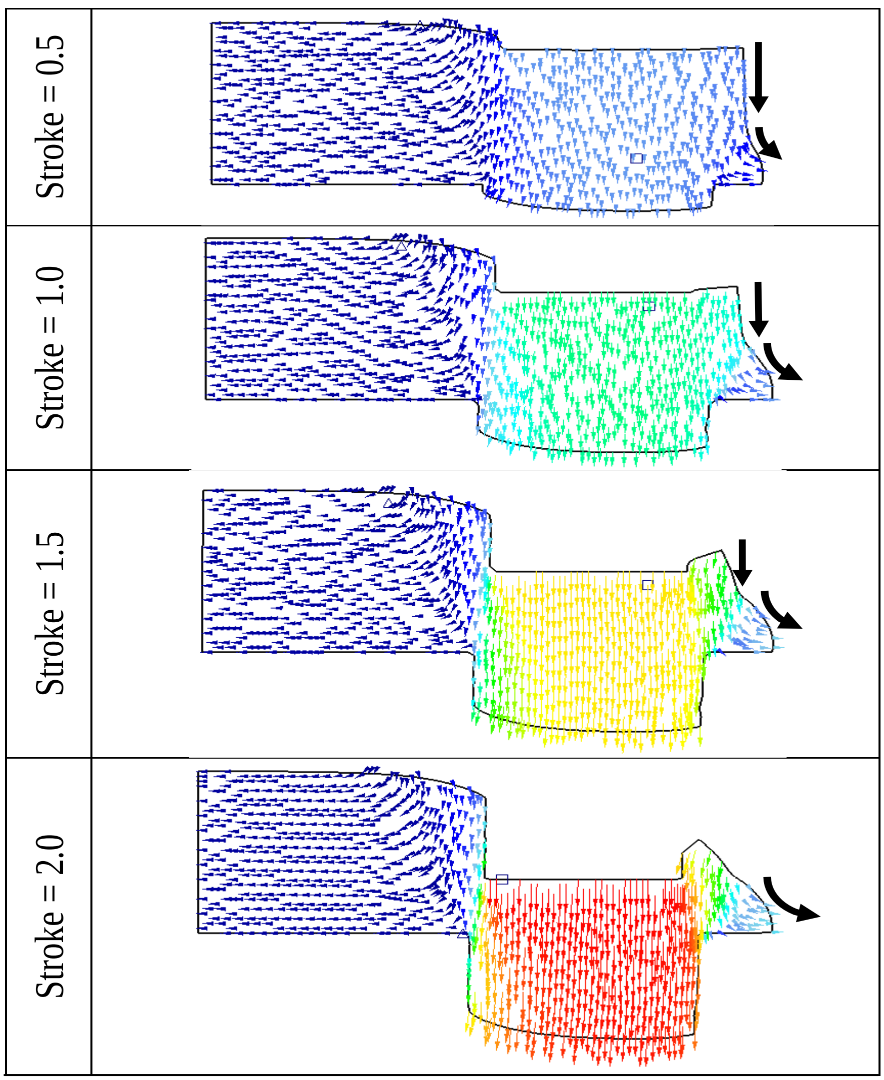

Figure 5. The material flow pattern of the pin head embossing at different punch stroke at diameter = 3 mm, distance to edge = 0.7 mm and depth = 2 mm.

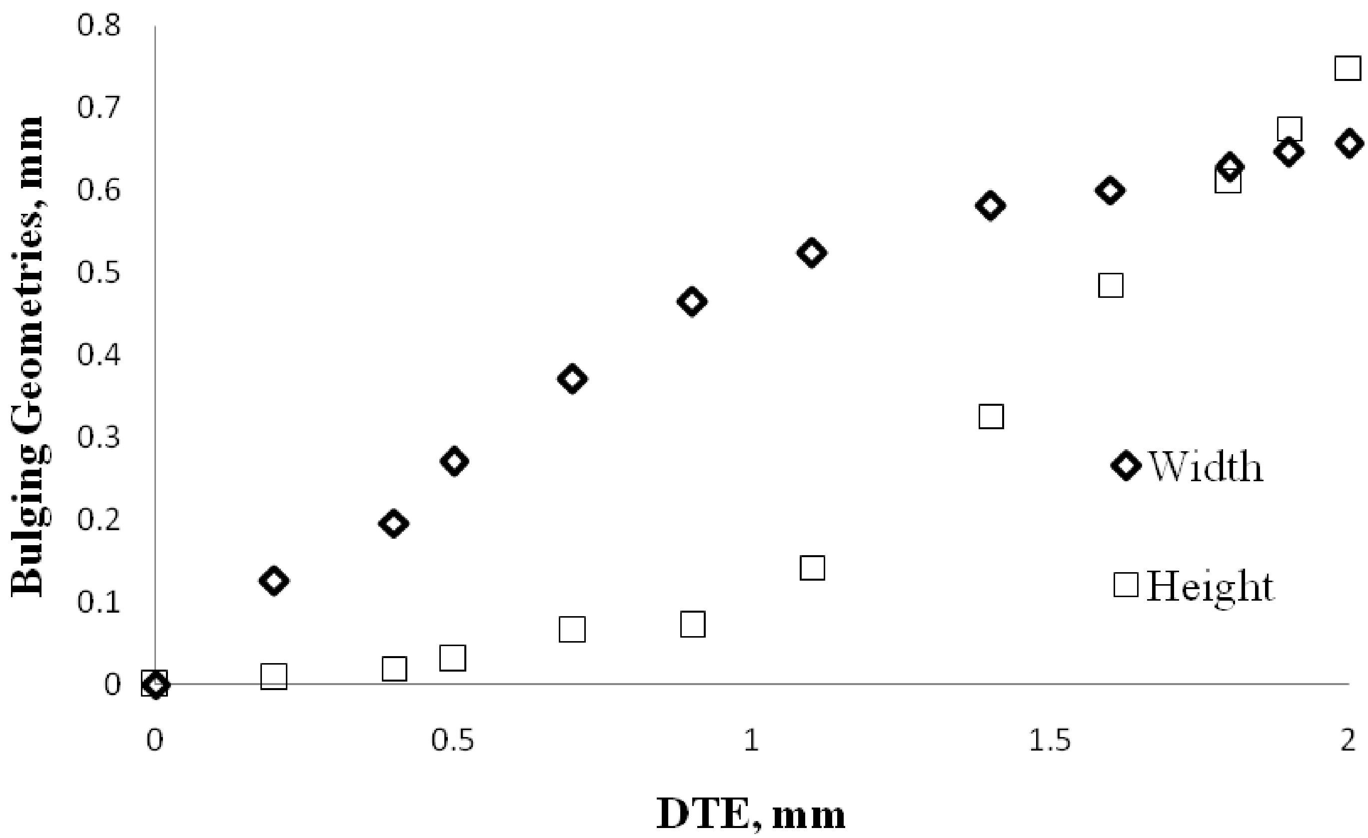

Figure 6. Relationship between bulging width and edge height to punch stroke.

The pin head is located toward one end of the workpiece; thus, the DTE factor is very crucial and the behavior of the material also differs from the normal case where the pin head is located at about the center of the workpiece. The DTE effect on the height and width of bulging can be seen in Figure 6. Figure 7 shows the material flow analysis of the investigated parameter DTE. Three different DTE values are used (0.7, 0.8, and 1.0), and the FE simulation results show a significant effect on the material flow analysis with respect to the punch stroke. Even at low punch strokes, the material begins to flow outward and is continuously forced to flow toward the edge until the end of the process. As a result, the height and width of the bulge increases. With increased DTE, the effect on the height of bulging can be clearly seen.

The under-filling is determined based on the filling ratio representing the completeness of the embossed region, as described in the previous section. The filling ratio is found to increase with increased DTE, as shown in Figure 8. For this case, the measured punch stroke starts from 0.5 mm. the blue square shows the predicted filling ratio, and the line indicates the exponential regression of the result.

Further comparison between the estimated and measured loads is performed, and the results are shown in Figure 9. The measured loads are obtained using a universal testing machine. The load patterns in both approaches show good agreement in terms of the maximum load, although different initial behaviors are observed. The discrepancy is attributed to the setup of the compression test and speed of compression.

Conclusion

The main objective of the paper was to investigate the effect of the punch location on pin head formation. 2D FE analysis was performed to investigate the cold embossing process of a pin head. The effect of the DTE on defect formation based on the material flow pattern was investigated. The DTE is found to have a significant effect on defect occurrence. The material tends to flow outward, resulting in the formation of bulging. Reducing the DTE value leads to decreased bulging size. Similar to the filling ratio, improvement in terms of the filling ability can be observed. With decreased DTE, the unfilling region is also reduced.

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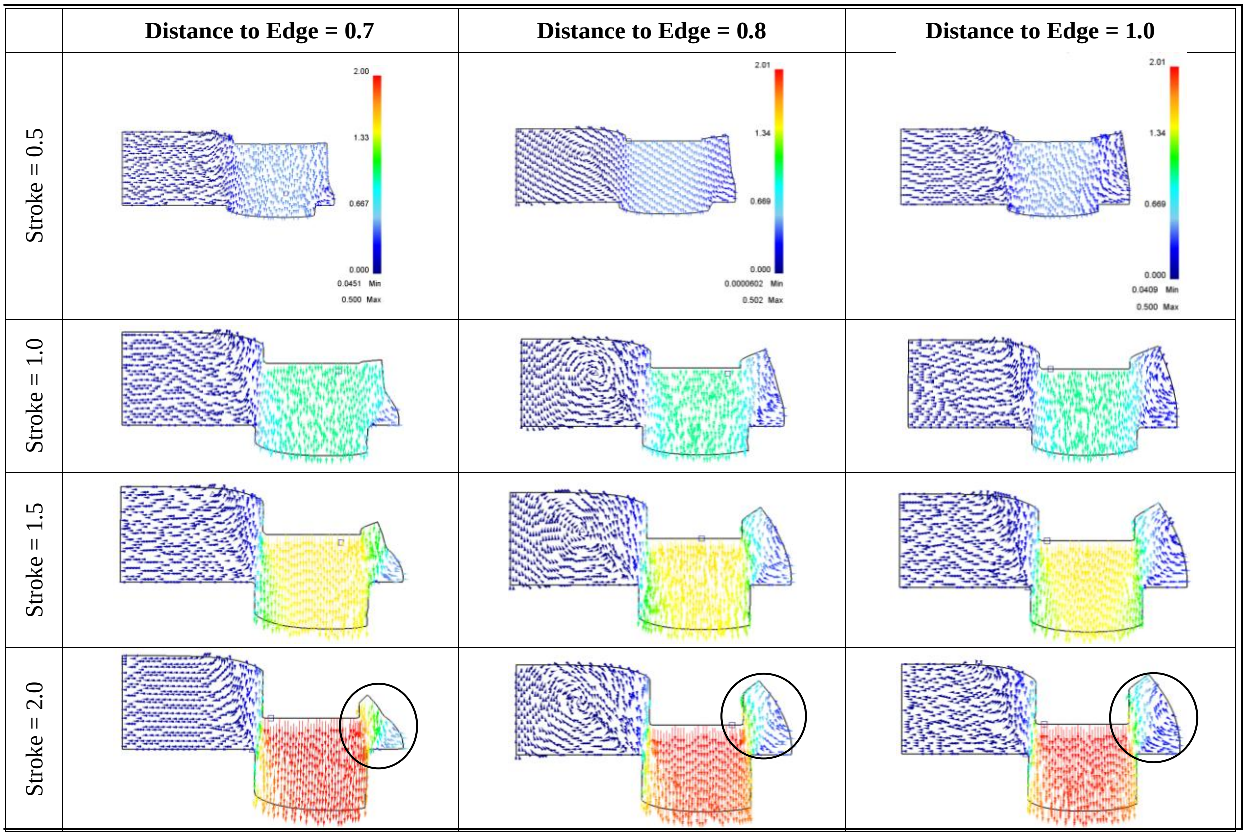

Figure 7. The effect of distance to edge in terms of material flow analysis at diameter = 3 mm and depth = 2 m.

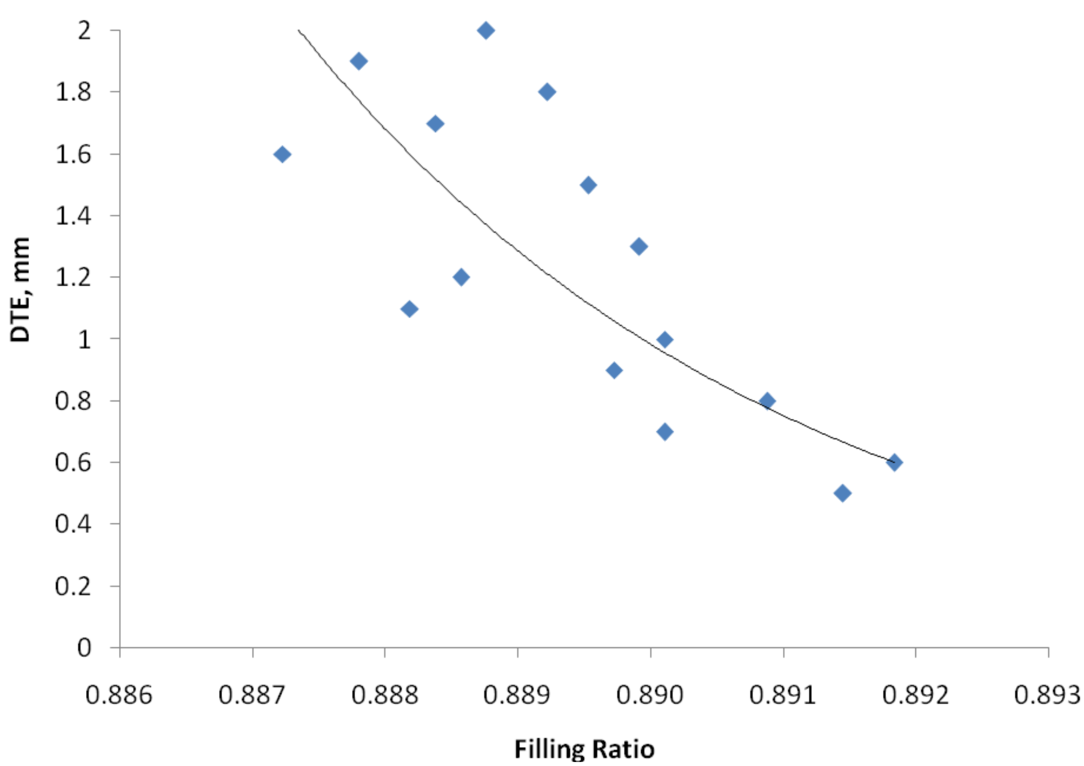

Figure 8. Effect of DTE to the filling ratio.

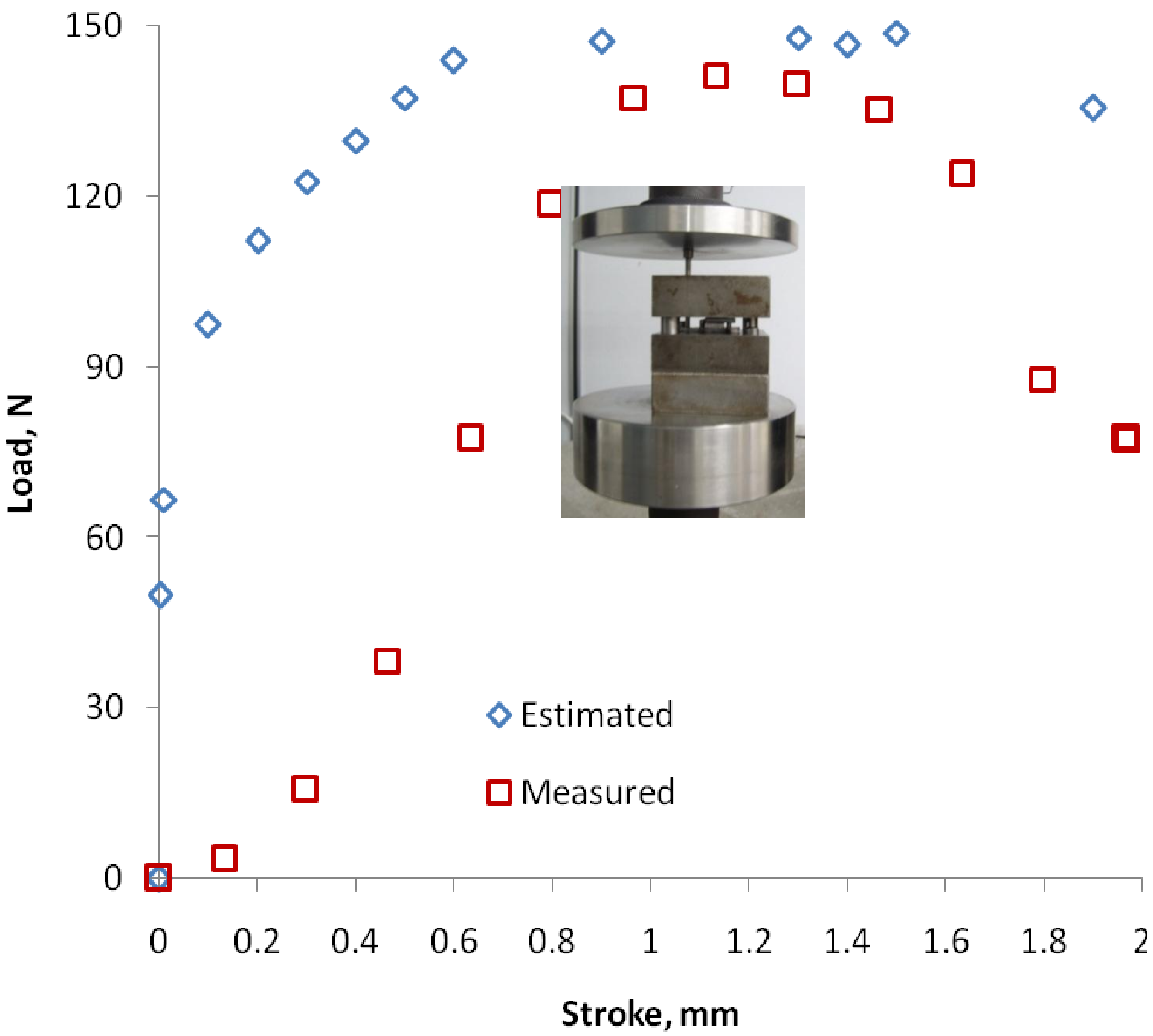

Figure 9. The comparison between the estimated and measured load.

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