Material Behavior Based Hybrid Process for Sheet Draw-Forging Thin Walled Magnesium Alloys

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Abstract. Magnesium alloys are conventionally formed at the elevated temperatures. The thermally improved formability is sensitive to the temperature and strain rate. Due to limitations in forming speeds, tooling strength and narrow processing windows, complex thin walled parts cannot be made by traditional warm drawing or hot forging processes. A hybrid process, which is based on the deformation mechanism of magnesium alloys at the elevated temperature, is proposed that combines warm drawing and hot forging modes to produce an aggressive geometry at acceptable forming speed. The process parameters, such as temperatures, forming speeds etc. are determined by the FEM modeling and simulation. Sensitivity analysis under the constraint of forming limits of Mg alloy sheet material and strength of tooling material is carried out. The proposed approach is demonstrated on a conical geometry with thin walls and with bottom features. Results show that designed geometry can be formed in about 8 seconds, this cannot be formed by conventional forging while around 1000s is required for warm drawing. This process is being further investigated through controlled experiments.

INTRODUCTION

Meeting the functional requirement at lowest possible weight is the goal for all industrial and electrical product design. In the IT industry, reduction of weight can improve the portability of the laptop or mobile phone while in the automotive industry, 0.5-0.7% fuel economy improvements can be obtained from 1% vehicle weight reduction. In the vehicle and electrical products, many parts have thin-walled geometries, e.g. gas tank, wheel disks, fender, decklid and electrical capacitor etc.. With low density of around 1.8g/mm$^3$, high specific strengths and electromagnetic interference shielding capacities, magnesium alloys are good candidates for the weight reduction purposes. Presently die casting is the primary process for manufacturing parts with complex geometry. However, the casting parts have lower mechanical properties, which are caused by the intrinsic die casting shortcomings, such as pin holes, porosity and cold shuts [1]. Forming processes, such as stamping and forging, are promising alternates for improving the mechanical properties of magnesium parts by offering fine-grained microstructure without porosity [2]. Unfortunately, the thermally improved formability is sensitive to strain rate, temperature and grain size. Complex magnesium components with deep thin-walls and/or bottom form features, can only be manufactured from sheets or rods at low strain rates ($\leq 10^{-2}$s$^{-1}$super plastic forming (SPF)) and/or at a fine grain size (grain refining technique). When the forming speed increases to the industrially accepted level (forming time less than 1 min, strain rate higher than $10^2$ s$^{-1}$) only simple geometries (round and rectangular) can be formed by sheet drawing or hot forging [2-5]. Due to the difficulties mentioned above, these parts are still essentially formed from steel or aluminum sheets.

FIGURE 1. Illustration of hybrid process

In order to solve the problems mentioned above, a hybrid process is proposed [6] in which a sheet preform is first created from a sheet blank by warm drawing and trimming; then the drawn sheet is hot forged to the final geometry, see the part geometry development shown in FIGURE 1. The sheet drawn preforms not only eliminate the die filling problem by
facilitating the metal flow but also reduce the temperature generation by reducing the plastic deformation.

![Cross section view and 3D view of a conical geometry](image)

**FIGURE 2.** Geometry for process development

A conical geometry with thin-walled and bottom form features such as in **FIGURE 2**, which cannot be made in Mg alloys by either drawing (cold or warm) alone or forging alone (due to unacceptable die pressures and narrow forging window), is selected to demonstrate the process feasibility. This design is based on the fact that: 1) conical geometry is the preferred geometry for the benchmark study on sheet metal drawability, 2) it exhibits major sheet forming failure modes, such as the two types of wrinkling and fracture [7] and 3) have thin-walled and bottom form features. Finite element simulation based sensitivity analysis is conducted to determine the process parameters, such as temperature, punch speed, blank size, under constraints of tooling strength and forming limits, for both the drawing and forging stages. The forging process following the drawing develops the designed bottom and thin-walled features without sacrificing the forming speed and the preformed blank facilitates the metal flow, with the temperature and contact pressure in the formed part both kept at safe levels. Based on the magnesium material deformation mechanism, this paper gives the design of the process.

**MATERIAL BEHAVIOR AND PROCESS DEVELOPMENT**

Deformation mechanism and modeling

At the elevated temperatures (above 100°C), CHP structure Mg alloys have improved formability by activating additional slip pyramid planes and the occurrence of twinning [1]. The improved ductility is sensitive to temperature and forming speed in which the equivalent strain at fracture decreases with the increase of strain rate and decrease of temperature (increasing Zener-Holloman parameter). Flow stress at the elevated temperature and variation of strain rate is described by the spittle constitutive equation, see **TABLE 1**. Magnesium alloy AZ31B with Young’s modulus of 44.8GPa and Poisson’s coefficient of 0.35, which is frequently used in both stamping and forging, is chosen for this study. The rheological parameters listed in **TABLE 1** are determined inversely from tensile and upsetting tests, respectively. Numerical models are created in a coupled thermo-elastic-plastic commercial finite element software FORGE2Dv4.0&v3.0, to demonstrate the approach proposed in this study. The tooling (punch, binder and die) is modeled as rigid bodies while the workpiece (initial sheet blank and forging preform) is modeled as elasto-viscoplastic solid. Given the symmetry of the problem, one half of the geometry is only modeled [6]. Interfacial friction coefficient is selected to be 0.1 for drawing [5] and 0.2 for extrusion [4]. M2 and H13 are chosen as tooling materials in drawing and forging. The thermal properties, such as heat capacity, interfacial heat transfer coefficient and convection coefficient, are taken at 1.7675 (N/mm²°C), 4.5 (N/s mm ºC) and 0.03 (N/s mm ºC), respectively [8].

**Deformation mode effect on forming limit**

Similar to other polycrystalline metal with CHP structure, the deformation of magnesium alloys is caused by the resolved shear stress sliding atoms while the norm stress pulling or compressing the atoms apart or close. Thus, free-straining deformation mode (drawing) and constrain-straining deformation mode (forging) have different ductility and forming limitations as summarized in **TABLE 2**. The improved ductility at the free-straining mode ($\dot{\varepsilon}=0.3$–0.8) is only available at significant low strain rate ($\dot{\varepsilon}=0.01$–0.002 s⁻¹) and around 20 minutes are required to draw a conical cup with shape and dimension shown in the **FIGURE 1** from a sheet blank (height to diameter ratio (HDR) =1.2mm/210mm) at a speed of 0.06mm/s. With the increase of hydrostatic pressure, ductility improved to a higher level ($\dot{\varepsilon}>4.0$). The small safe temperature window (300°C – 400°C) and the die filling are the limitations of the process[4, 9]. This phenomenon has been observed in the forging of the conical from a billet with a HDR=5.46mm/120mm, the process could fail because the die filling pressures reach 3400MPa which are much beyond the tooling strength of around 1500 MPa for hot working die steels.
At the given forging condition, die filling problem can be solved by changing the preform geometry (preceding drawing stage) while source of temperature generation is major caused by plastic deformation and friction, thus can be reduced by the deduction of plastic deformation and contact pressure [9, 10].

The preform's effect in forging the selected conical geometry has been conducted to investigate the feasibility of forging the drawn sheet. Different blank geometry with HDRs (ranging from 5.4/120=0.045 to 2.2/188=0.012) are formed in the FEM simulations. As the metal flows easily, the die filling height increases with the decrease of HDR, see FIGURE 3a. Here, 1500MPa is chosen as the strength limit of die material H13. The reduction of forming pressure and plastic deformation, see FIGURE 3b and c, leads to the reduction of maximum temperature on the formed part with the decrease of HDR value, see FIGURE 3d.

<table>
<thead>
<tr>
<th>TABLE 1. Material properties of AZ31B (note: rheological parameters from tensile tests [2] and compression tests [4])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Tensile</td>
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<tr>
<td>Compression</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE 2. Comparison on drawing and forging modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Items</td>
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<tr>
<td>---</td>
</tr>
<tr>
<td>Ductility</td>
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<td>Strain rate</td>
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<tr>
<td>Forming energy</td>
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<tr>
<td>Material distribution</td>
</tr>
<tr>
<td>Failure type</td>
</tr>
<tr>
<td>Geometry</td>
</tr>
</tbody>
</table>

**FIGURE 3.** Blank geometry effect on (a) contact pressure (b) die filling (c) strain and (d) temperature
**Process design**

The procedure for the design of the proposed hybrid process is composed of four steps and is carried out sequentially as shown in the **FIGURE 4**.

**FIGURE 4.** Procedure for design hybrid process

**Step 1:** With the help of the reverse unfolding calculation function provided by the PAM-STAMP2G, the required sheet blank size is determined (for the conical geometry in **FIGURE 2** it is 61041.6 mm$^3$).

**Step 2:** With the selected blank volume, the different blank sizes are determined by the equation, $V = H \pi (D/2.0)^2$. Six thickness variations (2.2 to 5.0 mm) are explored. The sensitivity analysis results are shown in **FIGURE 3**. Based on these results, the blank size is chosen at H/D=2.2mm/188.0mm.

**Step 3:** Now the parameters in the drawing stages (warm drawing and hot drawing) are determined. The diameter is increased to 210mm to prevent buckling. Process parameters, such as initial temperature of blank and tooling, moving speed of the punch, are determined through sensitivity analysis on temperature and forming speed. **FIGURE 5a and b** give the effect of temperature (blank, binder, die and punch at same temperature) and cold punch effect on the maximum strain at the draw depth of 16mm. Cold punch can reduce the maximum strain by strengthening the cup wall. This confirms to the conclusions given in [8]. Consequently, the temperature for the sheet, binder and die is set at 200ºC while punch temperature is set at 50ºC for the relative high forming speed (>3mm/s) in the warm drawing stage. The speed effect on the maximum strain at the draw depth of 40mm is given by the curve ‘a’ in **FIGURE 5c**, which shows that the maximum strain increase from 0.23 to 0.26 when the strain rate increases from 0.01 to 1 s$^{-1}$ corresponding to speed range from 1 to 100mm/s. The curve ‘b’ in **FIGURE 5c** gives the fracture equivalent strain at the strain rate 0.002 to 2.0 s$^{-1}$. The optimal speed for the warm drawing is determined by the cross point A ($\dot{\varepsilon} = 0.2$. $v=20$mm/s) of the curve ‘a’ and curve ‘b’, **FIGURE 5c**. Temperature is increased to 300ºC to obtain higher ductility for hot drawing stage. Similar to the warm drawing stage, the optimal speed is chosen at the cross point B ($\dot{\varepsilon} = 0.075 / v=0.8$mm/s), **FIGURE 5d**.

**Step 4:** Next the parameters of hot forging stage are established. The required forming pressure cannot exceed the strength of the tooling material H13, 1540MPa at 400ºC. The safe forming temperature window for the magnesium is from 300ºC to 400ºC. The temperature effect at the extrusion stage is studied by varying the tooling temperature simultaneously from 250 to 325ºC with the punch speed kept at 5mm/s, see **FIGURE 6a and b**. From this it can be seen: 1) the increase of tooling temperature level drops the maximum contact pressure and increases the temperature in the forged part; 2) at temperature of 300ºC, both pressure and formed part temperature are within the safe range (300ºC – 400ºC). The effect of punch speed effect is studied by varying punch speed from 1 to 20mm/s with the temperature fixed at 300ºC, **FIGURE 6c and d**. From this it can be concluded: 1) the increase of punch speed increases both forming pressure and part temperature; 2) 5mm/s is the maximum speed for obtaining a failure free part. Thus, tooling temperature of 300ºC and a punch speed of 5mm/s are chosen for the hot forging stage.
a. temperature effect on the maximum strain

b. cold punch effect on the maximum strain

c. determination optimal strain rate for warm drawing stage (binder, die, blank T=200ºC, punch T=50ºC)

d. determination of optimal strain rate for hot drawing stage (T=300ºC)

FIGURE 5. Determination optimal strain rate for the drawing

a. temperature effect on contact pressure

b. temperature effect on forged part temperature

c. punch speed effect on contact pressure

d. punch speed effect on forged part temperature

FIGURE 6. Sensitivity study on the hot forging
### TABLE 3. Process parameters for the hybrid process

<table>
<thead>
<tr>
<th>Stages</th>
<th>Punch Temp. (°C)</th>
<th>Die Temp. (°C)</th>
<th>Binder Temp. (°C)</th>
<th>Sheet Temp. (°C)</th>
<th>Max. EQ. Strain</th>
<th>Punch speed (mm/s)</th>
<th>Stroke (mm)</th>
<th>Time (s)</th>
<th>Developed wall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WD</td>
<td>50</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>0.25</td>
<td>20</td>
<td>40</td>
<td>2</td>
<td>40</td>
</tr>
<tr>
<td>HD</td>
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<td>300</td>
<td>300</td>
<td>300</td>
<td>0.4</td>
<td>0.8</td>
<td>4.8</td>
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</tr>
<tr>
<td>HF</td>
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<td>300</td>
<td>303-390</td>
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<td>5</td>
<td>1.2</td>
<td>0.24</td>
<td>16.0</td>
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</tr>
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<td>8.24</td>
</tr>
</tbody>
</table>

### SUMMARY

The proposed hybrid process produces part by warm drawing (WD), hot drawing (HD) and hot forging (HF) stages. Process parameters determined in the section 2 and corresponding forming results are listed in TABLE 3. By applying the designed process parameters, the proposed geometry is formed in the numerical simulation test in 8.24s. The geometry development during the forming process is given in the FIGURE 1 and iterative design processing FIGURE 5.

In this study, the developed process improves both formability and forming speed of the magnesium alloy by: 1) facilitating the metal flow and reducing the plastic deformation in the forging stage by drawing preform from well designed sheet; 2) improving ductility at the high forming speed by developing thin-wall at the forging. The other benefits of the process can be summarized as: 1) less heating time is required to obtain uniform temperature distribution in the preform; 2) providing more opportunity to tailor feature thicknesses to functional requirements and reducing component weight; 3) the parts formed in the hydrostatic pressure thus have high degree of integrity [9, 11]. In future investigation, the proposed process will be applied on more complex geometry and verified by conducting experiments.

### ACKNOWLEDGMENTS

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### REFERENCES

6. Z.Q. Sheng, R. Shivpuri, Investigation on a hybrid-process for manufacturing thin walled magnesium parts, ICPT 2005, October 9-13, Verona, Italy
9. R. S. Busk, Magnesium products design, New York, Marcel Dekker, c1987