# A study of sheet metal stamping processes of lightweight parts

February 2008 Tan Chin Joo

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Chapter 1 Introduction

Control of thickness distribution of stamped products for reduction in weight

- Welding lines
  - Long welding lines & high material loss
  - Tailor welded blank

- One-dimensional distribution
  - Tailor rolled blank

Proposed method for reduction in weight

- Flat
  - Local thickening
  - Small thickness blank

- Stamping

- Lightweight
  - Small thickness: low strength
  - Large thickness: high strength

- Proposed method for reduction in weight
Forming of lightweight material for reduction in weight of parts

**Magnesium alloy**

**Advantages**
- Density: 1/4 of mild steel
- Specific strength: 2 times of mild steel

**Disadvantages**
- Low formability at room temperature
- Formed at elevated temperature
- Heating apparatus is expensive and complicated
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Chapter 2
Multi-stage stamping of wheel disk having large inner corner thickness by means of conical punch

Forming process of steel wheel
Relationship between weight of wheel and fuel consumption

- Wheels directly driven by engine
  - Reduction in weight of wheel
  - Less fuel consumption
Target portion of wheel disk for local thickening

- Steel wheel
- Disk
- Rim
- Drive shaft
- Hat portion
- Inner corner
- Cracks in fatigue test
- Forming of lightweight disk
- Local thickening at
  - Strength ↑
  - Fatigue life ↑
  - Blank thickness ↓

Conventional multi-stage stamping of wheel disk

(a) 1st stage
(b) 2nd stage
(c) 3rd stage
(d) 4th stage
(e) 5th stage

- Flat punch Die
- Inner punch Outer punch Inner die Outer die
- Middle punch Die
- Decrease in thickness
- Equal

Drawn cup with flange
Increase in wall thickness at inner corner by means of conical punches

~ 1/3.5 actual size of wheel disk

Equivalent to inner corner

Conical punch
Blank holder
Die

(a) 1st stage

Conical punch
Die
Increase in thickness

(b) 2nd stage

Inner punch
Outer punch
Large compression

(c) 3rd stage

Inner die
Outer die

Parameters for increase in thickness

1. Punch angle, $\theta$
2. Drawn volume ratio
Relationship between drawn volume ratio and punch stroke

Drawn volume ratio, $V_r$
- ▼ 0.47
- △ 0.41
- □ 0.44
- ○ 0.38

Punch stroke in 2nd stage / mm

Punch angle □ / □

Total volume, $V_T$
Conical punch
Die

Drawn volume, $V$
After 2nd stage

$V_r = V / V_T$
Deformation behaviors for $\theta=0^\circ$ and $V_r=0.44$

(a) 1st stage

(b) 2nd stage

(c) 3rd stage
Deformation behaviors for $\theta=25^\circ$ and $V_r=0.44$

(a) 1st stage
(b) 2nd stage
(c) 3rd stage
Cross sections for $\theta = 25^\circ$ and $V_r = 0.44$

(a) 1st stage
(b) 2nd stage
(c) 3rd stage
(d) 4th stage
(e) 5th stage

$\sim 1/3$ of 13 inch wheel disk
Thickness distributions of drawn cup having $V_r = 0.41$ for $\theta = 0^\circ$, $20^\circ$ and $30^\circ$.

Change in wall thickness:

$$\frac{(t - t_o)}{t_o} \times 100\%$$

(a) Calculated

(b) Experiment
Thickness distributions of drawn cup having $V_r = 0.44$ for $\theta = 0^\circ$, $20^\circ$ and $30^\circ$.
Average increase in wall thickness at inner corner for $\theta = 0^\circ, 20^\circ, 30^\circ$ and different $V_r$. 

![Diagram showing the average increase in wall thickness at inner corner for different punch angles and $V_r$ values.](Diagram)

- Compression
- Stretching
Optimum forming condition for increase in wall thickness at inner corner of wheel disk

- Maximum increase in wall thickness at inner corner / %
- Maximum forming load in 3rd stage / kN
- Increase in thickness
- Forming load
- Optimum condition

- $V_r=0.47$
- $V_r=0.44$

Optimum condition for increase in wall thickness at inner corner of wheel disk.
Conclusions

Chapter 2
Multi-stage stamping of wheel disk having large inner corner thickness by means of conical punch

• Average 10% increase in wall thickness around the inner corner of the wheel disk was successfully obtained by means of the conical punches.

• The optimum forming conditions $\theta = 25^\circ$ and $V_r = 0.44$ were summarized.

• The blank thickness can be reduced without decreasing the strength of the wheel for the reduction in weight
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Chapter 3
Stamping of tailor circular blank for increase in wall thickness at inner corner of wheel disk

Disadvantages
- High material loss.
- Difficult to control laser welding process.
- High cost.
Stamping of tailor circular blank for increase in wall thickness at inner corner of wheel disk

- (a) 1st stage: Increase in thickness
- (b) 2nd stage: 2-stage stamping of tailor circular blank
- (c) 3rd stage: 3-stage forming of drawn cup with flange
Conditions for local thickening process

Parameters:

i) Stroke, s
ii) Clearance between punch and die, c

(a) 1st stage

Material was drawn into die cavity
Equivalent portion

(b) 2nd stage

Increase in thickness
Low compression
High compression
Restricted by friction

Die
Punch Blank holder
Blank holder
φ68
φ18
φ54
R8
R8

Deforming behavior for local thickening process (s = 6.5mm, c=2mm)

(a) 1st stage
Deforming behavior for local thickening process 
(s = 6.5mm, c=2mm)

(b) 2nd stage
Calculated effect of stroke in 1st stage of local thickening process

(c=2mm)
Effect of stroke in 2nd stage of local thickening process

(a) Calculated
(b) Experimental

(c=2mm)
Effect of clearance in local thickening process

Tailor circular blank was formed with the conditions $s = 6.5\text{mm}, c=2\text{mm}$
Forming load in 2nd stage and increase in wall thickness at target portion for different punch strokes in 1st stage (c=2mm)
Conditions for 3-stage forming of drawn cup with flange from tailor circular blank

(a) 1st stage

(b) 2nd stage

(c) 3rd stage

Tailor circular blank

1.6mm

~φ120

φ58.6
Punch

φ64.6

φ48.4
Punch

φ55.4

Blank-holder

13.5mm

15mm

~1
3.5

of actual disk

φ50.1
Inner punch

R2.0
R19.4

R8.0

φ36.82
Inner die

φ48.4
Blank-holder

φ55.4
Punch

φ50.1
Outer punch

φ58.6
Punch
Deforming behavior for 3-stage forming of drawn cup with flange from tailor circular blank
(s=6.5mm, c=2mm)
Deforming behavior for 3-stage forming of drawn cup with flange from tailor circular blank

(s=6.5mm, c=2mm)
Deforming behavior for 3-stage forming of drawn cup with flange from tailor circular blank

(s=6.5mm, c=2mm)
Wall thickness distribution of drawn cup with flange formed from tailor circular blank

Distance from bottom center / mm

Change in wall thickness %

Around inner corner

Hub hole
Chapter 3
Two-stage stamping of tailor circular blank for increase in wall thickness of wheel disk.

• Extra 8% increase in wall thickness at the inner corner of wheel disk was successfully obtained by the tailor circular blank.

• Extra 2 stages of the local thickening process were added to the conventional multi-stage stamping of wheel disk for the increase.

• The cross sectional shape of the drawn cup formed from the locally thick blank is almost the same with the one formed from the flat blank.
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Chapter 4
Multi-stage stamping of high strength steel wheel disk having large inner corner thickness

Forming conditions ($\theta = 25^\circ$ and $V_r = 0.44$)

$\sim 1/3.5$ actual size of wheel disk

(a) 1st stage
(b) 2nd stage
(c) 3rd stage

Equivalent to inner corner
<table>
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<th>Material properties</th>
<th>Mild steel</th>
<th>High strength steel</th>
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<td><strong>Tensile strength / MPa</strong></td>
<td>408 MPa</td>
<td>590 Mpa</td>
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<tr>
<td><strong>Flow stress / MPa</strong></td>
<td>$\mu =629 \mu 0.15$</td>
<td>$\mu =943.7 \mu 0.18$</td>
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<tr>
<td><strong>Blank thickness / mm</strong></td>
<td>1.6</td>
<td>1.4</td>
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### Thickness Distributions of Mild Steel and High Strength Steel Drawn Cups

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<th>Distance from Center (mm)</th>
<th>Change in Wall Thickness (%)</th>
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<tr>
<td>0</td>
<td>Mild 1.6</td>
</tr>
<tr>
<td>20</td>
<td>High strength 1.4</td>
</tr>
<tr>
<td>40</td>
<td>High strength 1.6</td>
</tr>
<tr>
<td>60</td>
<td>High strength 1.6</td>
</tr>
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</table>

- **Less increase in thickness at inner corner!!!**

**Diagram:**
- Inner corner
- Hub hole
- Around inner corner
- Thickness / mm
- Change in wall thickness / %
Thickness distributions of drawn cups for different blank thicknesses

Blank thickness / mm
Max. increase in wall thickness at inner corner / %

Blank material = mild steel

Decrease in blank thickness lead to small increase in thickness at inner corner
Conditions for 2-stage stamping of tailor circular blank for high strength steel wheel disk

(a) 1st stage

- Punch
- Blank holder
- Die
- Equivalent portion
- Material was drawn into die cavity

Punch stroke $s$ is a parameter

1.4mm

(b) 2nd stage

- Punch
- Blank holder
- Restricted by friction
- High compression
- Low compression
- Increase in thickness

Equivalent portion
Deformation behaviors of 2-stage stamping of tailor blank for s=8.5

(a) 1st stage
Deformation behaviors of 2-stage stamping of tailor blank for s=8.5

(b) 2nd stage
Influence of punch stroke in 1st stage on amount of local thickening

Forming of tailor blank using $s=8.5\text{mm}$
Deformation behaviors of 3-stage stamping of tailor blank for s=8.5

Plastic equivalent strain

(a) 1st stage
Deformation behaviors of 2-stages stamping of tailor blank for s=8.5

(b) 2nd stage
Deformation behaviors of 2-stages stamping of tailor blank for s=8.5

Plastic equivalent strain

(c) 3rd stage
Thickness distributions of drawn cups formed from tailor and flat blanks

Inner corner

Amount of thickening becomes double !!!

Around inner corner

Change in wall thickness / %

Distance from center / mm

Tailor

Flat
Cross sections of miniature wheel disk formed from tailor and flat blanks

(a) Disk formed from flat blank

(b) Disk formed from tailor blank
Conclusions

Chapter 4
Multi-stage stamping of high strength steel wheel disk having large inner corner thickness

• The increase in wall thickness at the inner corner of the high strength steel wheel disk becomes small due to the decrease in blank thickness.

• The high strength steel wheel disk formed from the tailor circular blank has 2 times of degree of increase in thickness at the inner corner if compared to the one formed from the flat blank.

• The cross section of high strength steel wheel disk formed from tailor blank is almost the same with the one formed from flat blank.
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Chapter 5
Multi-stage stamping of tailor square blank for increase in wall thickness at bottom corner of square cup

Local thickening method

(a) After 1st stage
(b) After 2nd stage

1st thickened portion

1st thickening operation
Conditions for thickening operation

symmetry along vertical axis

Parameter

\[ \theta = 40^\circ, 45^\circ, 50^\circ, 55^\circ, 60^\circ \]

(c) Dimension of ditch in detail
Deformation behavior for multi-stage stamping of tailor square blank for $\square = 55$°

(a) 1st stage
Deformation behavior for multi-stage stamping of tailor square blank for $\theta = 55^\circ$

(b) 2nd stage
Deformation behavior for multi-stage stamping of tailor square blank for $V = 55$ □

(c) 3rd stage
Deformation behavior for multi-stage stamping of tailor square blank for $\theta = 55 \degree$
Deformed tailor square blank obtained from simulation for $\theta = 55^\circ$

Max. 33% increase in thickness

Bulging
Cross sections of tailor square blank after 1st thickening operation for different $\square$

(a) $\square = 50$ 
(b) $\square = 55$  
(c) $\square = 60$

Buckling
Thickness distributions of tailor square blank after 1st thickening operation for different \( \theta \)
Thickness distribution along 1st thickened portion of tailor square blank after 2nd thickening operation

Cross between 1st and 2nd thickened portions

Less increase in thickness due to bulging

Portion equivalent to inner corner
Deformation behavior for deep drawing of square cup from tailor square blank

(a) Conditions

(b) Deformation behavior
Cross sections of square cup formed from tailor blank and flat blank

(a) Formed from tailor blank
(b) Formed from flat blank
Thickness distribution of square cup formed from tailor square blank

Distance of bottom edge along X = 18 / mm

Change in wall thickness / %

Cup formed from tailor blank
Tailor blank
Cup formed from flat blank
Bottom corner
Chapter 5

Multi-stage stamping of tailor square blank for increase in wall thickness at bottom corner of square cup

- The tailor square blank was successfully formed by stamping process.

- The tailor square blank having maximum 33% increase in wall thickness at the portion equivalent to the bottom corners of the square cup was formed.

- The square cup formed from the tailor blank have 10% increase in wall thickness at bottom corners if compare to the one formed from flat blank having 17% decrease in wall thickness.
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Chapter 6
Two-stage stamping of cold drawn magnesium alloy cup having small bottom corner

Casing of laptop formed by hot stamping process

Disadvantage
• Heating apparatus is expensive and complicated
Conditions for two-stage stamping of cold drawn magnesium alloy cup having small bottom corner

(a) 1st stage
- Die
- Blank holder
- Coil spring
- Outer punch
- Inner punch
- Drawn cup
- Container

(b) 2nd stage
- Punch
- Blank holder
- Die
- Coil spring
- Outer punch
- Inner punch
- Drawn cup
- Container

1. Drawn ratio = 1.72
2. \( R_p = 5 \text{mm} \)
3. \( R_p = 1 \text{mm} \)
Deformation behavior for round magnesium cup having small bottom corner

(a) 1st stage
(b) 2nd stage
Cross sections of round magnesium cup having small bottom corner

(a) 1st stage

(b) 2nd stage
Height and bottom corner radius of round cup for different punch strokes in 2nd stage

- Calculated
- Height of cup
- Experimental
- Bottom corner radius
- Crack at bottom corner
- Limit for crack
- s=2.8mm

Punch stroke in 2nd stage / mm

Height of cup / mm

Bottom corner radius / mm
Introducing conical punch and ironing die in 1st stage of cold stamping of round magnesium alloy cup

Ironing ratio, \( a = \frac{t_0 - b}{t_0} \)

Maximum \( \square = 150 \square \)

Conical punch

Blank Holder

Blank

Drawing die

Ironing die

Crack

(a) \( \square = 140 \square \)
Cross sections of round magnesium cup obtained from experiment

(a) By flat punch for \( s = 2.6 \text{mm} \)

(b) By conical punch for \( s = 2.9 \text{mm} \)

(c) By conical punch for \( s = 3.4 \text{mm} \) and \( a = 20\% \)
Conditions for two-stage stamping of magnesium square cup having small bottom corner radius

(a) 1st stage

(b) 2nd stage
Magnesium square cups obtained from experiment

(a) 1st stage

(b) 2nd stage
Chapter 6
Two-stage stamping of cold drawn magnesium alloy cup having small bottom corner

• The round and the square magnesium alloy cups having small bottom corners were successfully formed at room temperature.

• An extra stage is added for reducing the bottom corner radius.

• The employment of the conical punch and the ironing die improved the dimensions of the cup.
List of publications

Reviewed journals:

Reviewed Conference papers:
Drawn cup for $\theta=25^\circ$ and $V_r=0.44$
Effect of angle of bulging ring in local thickening process

Max. increase in wall thickness in target portion / %

Angle of bulging ring $\theta$ / °
Reason for decrease in thickness for $s = 7.5\text{mm}$

(i) $s = 7.5\text{mm}$

(ii) $s = 6.5\text{mm}$

Equivalent portion

Die

Outer punch

Inner punch

Increase in thickness

High compression

Low compression

(c = 2\text{mm})
Photographs of deformed discs

(a) 1st stage
2-stages local thickening process ($s=6.5\text{mm}$, $c=2\text{mm}$)

(b) 2nd stage

(i) Formed from locally thick blank
(ii) Formed from flat blank

Drawn cup with flange
Thickness distributions of drawn cups for different materials

Blank thickness = 1.4mm

High strength steel has no influence on the increase in thickness.
Forming of high strength steel drawn cup from tailor circular blank

- 2-stage stamping of tailor circular blank
  - (a) 1st stage
  - (b) 2nd stage
- 3-stage forming of drawn cup with flange
  - (a) 1st stage
  - (b) 2nd stage
  - (c) 3rd stage
Forming load in 2nd stage for $s = 8.5\text{mm}$
Miniature wheel disks formed from tailor and flat blanks.

(a) Formed from flat blank

(b) Formed from tailor blank
Deformation behaviors of thickening operation for $\theta = 55^\circ$
Chapter 5
Multi-stage stamping of tailor square blank for increase in wall thickness at bottom corner of square cup

(a) 1st thickening operation
(b) 2nd thickening operation
Distribution of thickness and hardness of round cup in two-stage stamping process
Deformation behaviors of cup for $\phi = 150^\circ$

Plastic equivalent strain

- 0.549
- 0.506
- 0.463
- 0.420
- 0.377
- 0.334
- 0.291
- 0.248
- 0.205
- 0.162
- 0.119
- 0.076
- 0.033

(a) 1st stage
Deformation behaviors of round magnesium cup for $\theta = 150^\circ$

Plastic equivalent strain

<table>
<thead>
<tr>
<th>0.950</th>
<th>0.879</th>
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<td>0.808</td>
<td>0.737</td>
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<tr>
<td>0.666</td>
<td>0.596</td>
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<td>0.596</td>
<td>0.525</td>
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<tr>
<td>0.454</td>
<td>0.383</td>
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<tr>
<td>0.383</td>
<td>0.312</td>
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<tr>
<td>0.241</td>
<td>0.171</td>
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<tr>
<td>0.010</td>
<td></td>
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(b) 2nd stage
Relationship between height of cup and bottom corner radius for different punch strokes in 2nd stage for $a=20\%$ & $\theta = 150^\circ$.
Distribution of thickness strain and hardness of cup after 1st and 2nd stage for \( a = 20\% \) & \( \theta = 150^\circ \)
Distribution of thickness strain and of hardness along cross section of square cup

![Graph showing distribution of thickness strain and hardness along the cross section of a square cup. The graph plots distance from the bottom center in millimeters on the x-axis and thickness strain and hardness on the y-axis. The graph indicates variations in thickness strain and hardness around the bottom corner of the cup.]
Relationship between forming load in 3rd stage and conical punch angle

Forming load in 3rd stage / kN

Punch angle

$V_r = 0.47$

$V_r = 0.44$

$V_r = 0.41$

$V_r = 0.38$