Forming of High Strength Steel Sheets

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1. High strength steel sheet
2. Springback in bending
3. Stretch flangeability
4. Fracture
5. Galling and seizure
6. Wrinkling
7. Shearing
8. Tailored blank
9. Plastic joining

Cold Stamping of High Strength Steel Sheets

Forming of lightweight automobile parts

Reduction in 100 kg weight: 1km/

Material
- High strength steel sheet (7.8)
- Aluminium (2.7), Magnesium (1.8), Titanium (4.5)

Part
- Hollow parts
- One piece

Simulation
- Finite element method

Production of automobiles in countries

Unit: 10,000 cars

Environmentally friendly automobiles: Hybrid

Toyota Prius
Honda Fit-Jazz
Toyota Prius PHV

Environmentally friendly automobiles: Electric

Nissan Leaf
Mitsubishi i-MiEV
Tesla Roadster

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**CO2 emission for producing automobile materials**

<table>
<thead>
<tr>
<th>Material</th>
<th>CO2 Emission per producing 1 kg material (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel</td>
<td>2.3 ~ 2.7</td>
</tr>
<tr>
<td>High tensile steel</td>
<td>2.3 ~ 2.7</td>
</tr>
<tr>
<td>Aluminium</td>
<td>13.9 ~ 15.5</td>
</tr>
<tr>
<td>Magnesium (alloy)</td>
<td>19 ~ 24.8</td>
</tr>
<tr>
<td>Magnesium (pure)</td>
<td>40 ~ 45</td>
</tr>
<tr>
<td>Carbon fibers</td>
<td>21 ~ 23</td>
</tr>
</tbody>
</table>

**Specific strength for various sheet metals**

<table>
<thead>
<tr>
<th>Sheet</th>
<th>Tensile strength</th>
<th>Specific gravity</th>
<th>Strength-to-specific gravity ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra high strength steel</td>
<td>980 - 1470MPa</td>
<td>7.8</td>
<td>126 - 188MPa</td>
</tr>
<tr>
<td>High strength steel</td>
<td>490 - 790MPa</td>
<td>7.8</td>
<td>63 - 101MPa</td>
</tr>
<tr>
<td>Mild steel SPCC</td>
<td>340MPa</td>
<td>7.8</td>
<td>44MPa</td>
</tr>
<tr>
<td>Aluminium alloy A6061(T6)</td>
<td>310MPa</td>
<td>2.7</td>
<td>115MPa</td>
</tr>
</tbody>
</table>

**High strength steel sheets**

<table>
<thead>
<tr>
<th>Tensile strength /MPa</th>
<th>Elongation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP steel</td>
<td>30-40</td>
</tr>
<tr>
<td>TRIP steel</td>
<td>50-60</td>
</tr>
<tr>
<td>Ultra sheet</td>
<td>30-40</td>
</tr>
</tbody>
</table>

**Mechanism of strengthening of high strength steel sheet**

![Mechanism diagram](image)

- P<sub>max</sub>/A<sub>0</sub>
- A<sub>0</sub>: initial cross-sectional area
Properties of high strength steel sheets

ULSAB-AVC (Ultra Light Steel Auto Body - Advanced Vehicle Concept)

Application of high strength steel sheets to automobile body

36% of total weight

Used steel sheets

Results of ULSAB-AVC

<table>
<thead>
<tr>
<th>Fuel consumption</th>
<th>C-Class</th>
<th>PHG+Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>O-Km/Liter</td>
<td>4.4</td>
<td>3.2</td>
</tr>
<tr>
<td>CO₂ kg/km</td>
<td>1.05</td>
<td>0.68</td>
</tr>
<tr>
<td>Fuel consumption (g/km)</td>
<td>43.7</td>
<td>28.4</td>
</tr>
<tr>
<td>CO₂ kg/km</td>
<td>985</td>
<td>985</td>
</tr>
<tr>
<td>Weight</td>
<td>240</td>
<td>260</td>
</tr>
<tr>
<td>Collision safety</td>
<td>☆☆</td>
<td>☆☆</td>
</tr>
<tr>
<td>Production cost</td>
<td>$9150</td>
<td>$9500</td>
</tr>
</tbody>
</table>

- ULSAB-AVC: Ultra Light Steel Auto Body - Advanced Vehicle Concept
- High strength steel sheets are used for the automobile body, occupying 36% of the total weight.
- Different types of steel sheets are used for various parts of the body.
- Results of ULSAB-AVC include fuel consumption, weight, collision safety, and production cost.
Application of high strength steel sheets to automobile body

Subaru Legacy
Material percentage
- Mild Steel: 46%
- HSS: 36.4%
- Ultra HSS: 12.8%
- Aluminum: 4.8%

Toyota Crown, 45% of body panels

Mazda, Demio
High strength steel sheets: from 40% to 60%
8% reduction in weight

Mazda, Atenza, Roadstar
Mazda, Atenza: from 42% to 49%
Mazda, Roadstar, 1500MPa: 12% (green)

Chang in percentage of use of HSS
(a) 2004 (b) 2014

Use of HSS in automobile body panels

Increase in strength and reduction in weight

(a) 2004 (b) 2014

Pillar
Bumper
Inner panel
Outer panel

Increase in bending strength, %
0 20 40 60
0 1000 2000 3000 4000 5000
Tensile strength / MPa

Reduction in weight, %
0 20 40
0 500 1000 1500 2000
Tensile strength / MPa
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**Cold Stamping of High Strength Steel Sheets**

Springback in bending

- Ultra HSS
- Mild steel

Elastic recovery

Springback: large
Accuracy of shape: low

Loading: Compressive
Unloading: Tensile

Tensile
Compressive

Deterioration in shape accuracy of formed parts

Springback in hat-shaped bending of HSS

Springback in bending:

\[ \Delta \theta = \frac{M}{EI} \theta R = \frac{3\sigma R}{E t} \]

- \( \Delta \theta \): Springback
- \( M \): Bending moment \( (bt^2/4) \)
- \( I \): Geometrical moment of inertia \( (bh^3/12) \)
- \( \sigma \): Flow stress
- \( E \): Young's modulus
- \( t \): Thickness
- \( \theta \): Bend angle
- \( R \): Radius

Effects of material and thickness in V-shaped bending

(a) Material
(b) Thickness
Effect of strength on springback in hat-shaped bending

Effect of back pressure on springback in U-shaped bending

Effect of strength on wrap in hat-shaped bending

Effect of blank holder force on wrap in hat-shaped bending

800kN CNC Servo Press

Reduction in springback in V-shaped bending

Reduction in thickness in bottoming

\[ f = \frac{\Delta t}{t_0} \]
Deformation behaviour in V-shaped bending

(a) SPCC  (b) SPFC980Y

v=24mm/s, f=0%, T=0.5s
3 times slower

Flow stress curve of sheets at room temperature

Large springback

SPCC

SPFC440

SPFC980Y

A5083

A1050

Strain

SPCC

SPFC440

SPFC980Y

Flow stress /MPa

SPCC

SPFC440

SPFC980Y

A5083

A1050

Relationship between springback and forming speed in V-shaped bending (f=0%, T=0s)

SPC980Y, Nominal

SPC440

SPCC

Forming speed /mms⁻¹

Springback, A0°

0

2

4

6

8

0

10

20

30

40

50

Scatter of initial thickness of sheets

Sheet

SPCC

SPFC440

SPFC980Y

Nominal thickness 1.2mm

Number of sheets

Initial thickness t₀ / mm

0

10

20

30

40

1.18

1.19

1.2

1.21

1.22

Relationship between springback and forming speed in V-shaped bending (f=0%, T=0s)

SPC980Y, real

SPC440

SPCC

Forming speed /mms⁻¹

Springback, A0°

0

2

4

6

8

0

10

20

30

40

50

Relationship between springback and tensile strength

SPC980Y

SPCC

SPFC440

SPCC

SPFC440

SPFC980Y

590MPa

270MPa

Required tolerance ±0.5mm

Tensile strength /MPa

Springback mm

250

500

750

1000
Effects of bottoming and holding time at bottom dead centre for SPFC980Y

Distribution of stress in width direction just after unloading for finishing reduction in thickness

Effect of bottoming

Prevention of springback by beads in side wall

Prevention of springback by chamfering

Prevention of springback by control of blank holder force
Prevention of springback by crash forming

(a) Draw bending  (b) Crash forming without blank holder

Prevention of springback by overrun inducing punch

Prevention of springback by crash forming

Tensile strength /MPa

<table>
<thead>
<tr>
<th>Material</th>
<th>452</th>
<th>597</th>
<th>838</th>
<th>1025</th>
<th>1211</th>
<th>1520</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Prevention of springback by crash forming

(a) Drawing  (b) Restriking

980MPa

Drawing

Restriking
Prevention of springback by slide locking

(a) Drawing  (b) Slide locking

Prevention of springback and twisting by chamfered bending and push-back forming

590MPa, 1.0 mm

Adjustment of die shape by finite element simulation

(b) 1st adjustment

Effect of constitutive equations on calculated springback by finite element simulation

(a) Experimental result (980 MPa)

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Fracture in stretch flanging of high strength steel sheets

780MPa high strength steel formed product
Properties of high strength steel sheets

Steel sheets used for punching and stretch flanging

<table>
<thead>
<tr>
<th>Sheet</th>
<th>Thickness [mm]</th>
<th>Yield stress [MPa]</th>
<th>Tensile strength [MPa]</th>
<th>Elongation [%]</th>
<th>n-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>JSC980Y</td>
<td>1.41</td>
<td>620</td>
<td>1027</td>
<td>18.7</td>
<td>0.12</td>
</tr>
<tr>
<td>JSC780Y</td>
<td>1.41</td>
<td>558</td>
<td>823</td>
<td>19.0</td>
<td>0.12</td>
</tr>
<tr>
<td>JSC590R</td>
<td>1.40</td>
<td>446</td>
<td>600</td>
<td>26.2</td>
<td>0.14</td>
</tr>
<tr>
<td>JSC440W</td>
<td>1.41</td>
<td>320</td>
<td>455</td>
<td>33.8</td>
<td>0.18</td>
</tr>
<tr>
<td>JSC390W</td>
<td>1.39</td>
<td>283</td>
<td>389</td>
<td>35.8</td>
<td>0.18</td>
</tr>
<tr>
<td>JSC270C</td>
<td>1.39</td>
<td>223</td>
<td>333</td>
<td>41.2</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Shearing conditions

Stretch flanging conditions

Effect of clearance ratio of occurrence of fracture (JSC980Y, L=15mm)

Relationship between limiting flanging ratio and clearance ratio
Improvement of stretch flangeability by upper and lower punching

(a) Initial  
(b) Shearing by upper punch  
(c) Shearing by lower punch  
(d) Punching

Relationship between limiting expansion ratio and tensile strength

Conventional  
(c=20%t)

Smoothing of fracture surface on sheared edge with conical punch

Shearing  
Smoothing  
Stretch flanging

Sheared edge  
Tensile

Smoothing of fracture surface on sheared edge of punched sheet (JSC980Y)

(a) P=0 kN  
(b) P=6 kN  
(c) P=12 kN  
(d) P=16 kN  
(e) P=20 kN  
(f) P=22 kN

Smoothing of fracture surface on sheared edge with conical punch in punching

Punching load P  
Conical punch

Guide  
Sheet holder

Blank (c=20%)  
Die

30°  
φ10.72

Smoothened sheared edge (JSC980Y)

(i) Surface  
(ii) Height

(a) P=0kN (Punched edge)  
(b) P=22kN
Improvement of limiting expansion ratio by smoothing (JSC980Y)

Sheared edge after smoothing (JSC780, c=20%)

Sheared edge before and after smoothing (JSC980Y, c=15%)

Improvement of limiting stretch flanging ratio (JSC780, c=20%)

Improved of limiting stretch flanging ratio (JSC980Y, c=15%)
**Reduction in tensile stress at corner using gradual contact punch**

(a) Before forming  
(b) During forming  
(c) After forming

**Shearing conditions**

<table>
<thead>
<tr>
<th>Sheet</th>
<th>Thickness /mm</th>
<th>Yield stress /MPa</th>
<th>Tensile strength /MPa</th>
<th>Elongation %</th>
<th>Reduction in area %</th>
<th>n-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>JSC780Y</td>
<td>1.4</td>
<td>395</td>
<td>847</td>
<td>18.8</td>
<td>66</td>
<td>0.15</td>
</tr>
<tr>
<td>JSC980Y</td>
<td>1.4</td>
<td>660</td>
<td>1014</td>
<td>16.4</td>
<td>45</td>
<td>0.15</td>
</tr>
<tr>
<td>JSC1180Y</td>
<td>1.2</td>
<td>864</td>
<td>1209</td>
<td>10.8</td>
<td>46</td>
<td>0.14</td>
</tr>
</tbody>
</table>

**Stretch flanging conditions**

**Calculated conditions of stretch flanging**

- **Software**: LS-DYNA
- **Symmetry**: 1/2 model
- **Sheet**: Elastic-plastic shell elements
- **Tools**: Rigid
- **Coefficient of friction**: 0.15
- **Punch speed**: 100mm/s

**Distribution of longitudinal strain by flat punch** (JSC780, α=0°, L=18mm)
Distribution of longitudinal strain by gradual contact punch (JSC780, α=10°, W/W₀=1.0, L=17mm)

(a) Flat punch (α=0°)  
(b) Gradual contact punch  
(α=10°, W/W₀=1.0)

Prediction of fracture at corner of 780MPa sheet using gradual contact punch

(a) Flat punch (α=0°)  
(b) Gradual contact punch (α=10°, W/W₀=1.0)

Prediction of fracture at corner of 980MPa sheet using gradual contact punch

(a) Flat punch, α=180°  
(b) Gradual contact punch,  
α=170°

Improvement of limiting flange height by gradual contact punch

(a) JSC980Y  
(b) JSC1180Y