

EXPERIMENTAL AND NUMERICAL ANALYSIS ON SHEET HYDROFORMING PROCESS OF ALUMINUM ALLOYS

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ABSTRACT – Hydroforming process for aluminium alloy sheets have been largely accepted by automotive industries for the production of components characterized by good surface quality, high dimensional accuracy together with high drawing ratio and complex shape. However, the process parameters with its stress distribution have not fully studied. The main aim of this research is to compare the residual stresses between experiment and finite elemental method in order to predict the stress development after hydroforming process.

1. INTRODUCTION

As the environmental regulations such as CO₂ emission limit for vehicles becomes strict, the automotive industry is going forward to reduce the weight of vehicles by using light metals for body structure. However, since the formability of light metals such as aluminium alloy is not as good as that of steel, various new forming techniques have been introduced. Hydroforming is the process that metal sheets are formed to the defined shape by high fluid pressure, and it relies the forming condition on the high fluid pressure to achieve the designed shape (1). As shown in Fig 1, for hydroforming process, the metal sheet is placed on the internal pressure pot, and high fluid pressure deforms the metal sheet. There are lots of advantages in hydroforming process. First, since matching dies are not needed, the irregularly contoured shapes are easily formed, and it can save the tool costs. In addition, it provides high surface finish and produces the formed sheet with a high precision.

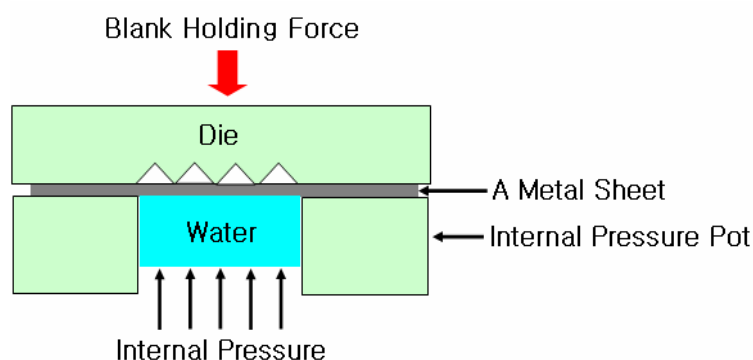


Figure 1. The schematic diagram of hydroforming process

During metal forming processes, stresses are developed by a forming pressure whether it is conventional forming processes or new forming processes. The stresses of metal sheets are dependent on its forming condition. They also affect the amount of spring back and following forming condition.

However, the process parameters with its stress distribution have not fully studied. Since predicting the stress development of automotive panels during a forming process is important for structural components and its post heat treatment, in this research, residual stress analysis by x-ray measurement and finite element method have been carried out.

2. EXPERIMENTAL PROCEDURE

The aluminium sheets used in this research is Al-5%Mg alloy, and their size was 320mm by 500mm with 1mm thickness. The forming force operated on the surface of the sheet was 7,200kN, which is 450bar in pressure. Fig 2 shows the die with V-shaped profiles. It was designed to study the forming limit with various radiuses from 1mm to 7mm at the bottom of the profile.

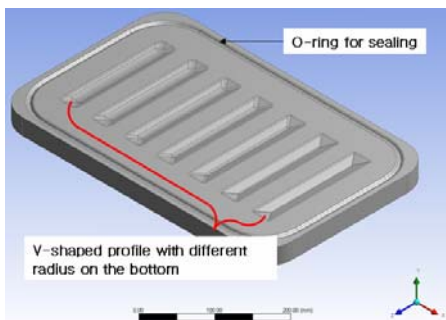


Figure 2. The schematic picture of V-shaped profile in the die

The aluminium sheet was removed from the die after hydroforming process, and the residual stresses were measured by XSTRESS-3000 system as shown in Fig 3. The measuring power was about 28kV and 6mA, and the x-ray exposure time was 40seconds. The angles of rotation (φ) during the measurement were 0° , 45° , and 90° , and the angles (ψ) between measurement step were 0° , 22.5° , and 45° . φ is the angle between a fixed direction in the plane of the specimen and the projection in that plane of the normal to the diffracting planes, and ψ is the angle between the normal of the specimen and the normal of the diffracting planes (Fig 4 and Fig 5).

Also, since x-ray stress measurement should have diffraction peak in high back reflection area, 156° of reflection angle for aluminium was set up.

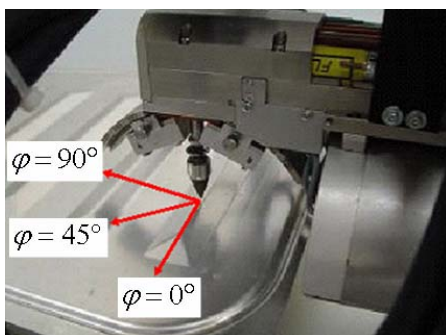


Figure 3. The picture of residual stress measurement system

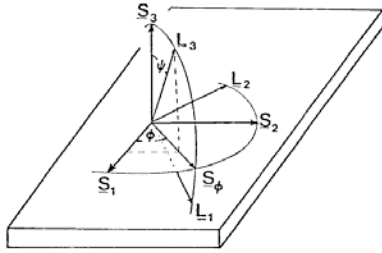


Figure 4. The angles for x-ray measurement system(1)

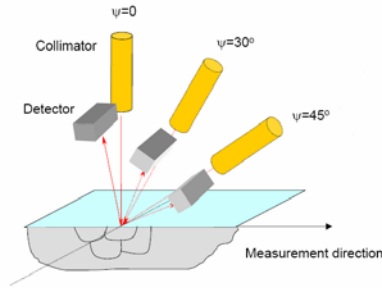


Figure 5. The angles of x-ray measurement system(2)

The height and radius of V-shaped profile of the hydroformed aluminium sheets were measured by 3D coordinate measurement system, and it was calculated by the method of least square formula.

The finite elemental analysis has been carried out with LS-DYNA, the explicit code module of ANSYS. The die was set as a rigid body, and the size of mesh for the aluminium sheet was 1mm in each length, which is smaller than the radius of the bottom of V-shaped profile. The boundary condition was set up, so that the formed area is symmetry. In addition, contact condition was surface to surface contact, and static friction coefficient for stress calculation was 0.01, and dynamic friction coefficient 0.01. The aluminium sheet was defined as a shell model.

3. RESULTS AND DISCUSSION

3.1. HYDROFORMING PROCESS

Fig 6 shows the process that a white painted aluminium sheet was hydroformed (Fig 6, (a) and (b)), and then, the profile in the die was examined in such a way that there is any white paint spotted from the aluminium sheet. Such examinations can tell that the aluminium sheet was completely deformed along the die profile. For the 1mm radius profile, white paint was not spotted on the top, while for the 7mm one, white paint was spotted all over the profile. Thus, it can be explained that for the 1mm radius of profile, the aluminium sheet was not filled since the fluid pressure is not large enough to form (Fig 7).



Figure 6. (a) Al sheet before hydroforming, (b) Al sheet after hydroforming, (c) 1mm radius profile after hydroforming, and (d) 7mm radius profile after hydroforming

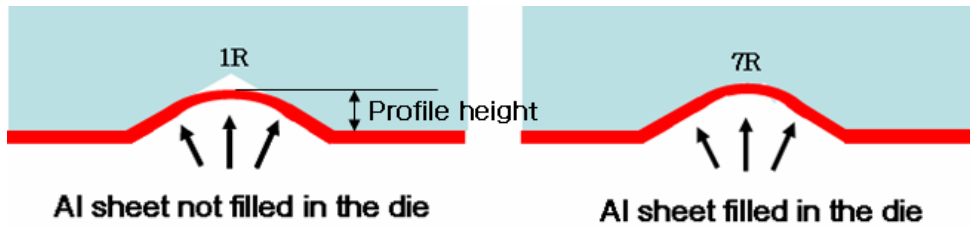


Figure 7. The schematic picture of Al sheet deforming during hydroforming

Table 1 and 2 show the results of height and radius of the V-shaped profile on the hydroformed aluminium sheet. From the results of profile height, it can be expected that smaller than the 6mm radius, higher pressure is needed to deform the sheet into designed shape. Also the results of profile radius shows that the designed radius was not achieved on all profiles.

Table 1. The height (mm) of the V-shaped profile of hydroformed aluminium sheet

	1R	2R	3R	4R	5R	6R	7R
Designed Profile Height (die)	4.95	4.88	4.82	4.78	4.73	4.67	4.61
Measured Profile Height (Al sheet)	3.86	4.30	4.48	4.41	4.28	4.20	4.51

*1mm of radius = 1R, 2mm of radius = 2R, ... 7mm of radius = 7R

Table 2. The radius (mm) of the V-shaped profile of hydroformed aluminium sheet

	1R	2R	3R	4R	5R	6R	7R
Designed Profile Radius (die)	1	2	3	4	5	6	7
Measured Profile Radius (Al sheet)	6.75	6.80	6.91	7.02	7.29	7.41	8.2

3.2. X-RAY STRESS MEASUREMENT

The basic condition for stress measurement by x-ray diffraction is that the specimens for the measurement should be crystalline materials with small grain size and randomly oriented grains. In general, it should have diffraction peak in high back reflections area (higher than 130°) and known elastic constants.

On the basis of elastic theory, in a macroscopically isotropic crystalline material, the formula for the strain in the direction defined by the angles φ and ψ is expressed

$$\begin{aligned}
 \varepsilon_{\varphi\psi} &= \frac{d_{\varphi\psi} - d_0}{d_0} \\
 &= \frac{1}{2} s_2^{hkl} [\sigma_{11} \cos^2 \varphi + \sigma_{12} \sin 2\varphi + \sigma_{22} \sin^2 \varphi - \sigma_{33}] \sin^2 \psi \\
 &\quad + \frac{1}{2} s_2^{hkl} \sigma_{33} - s_1^{hkl} [\sigma_{11} + \sigma_{22} + \sigma_{33}] \\
 &\quad + \frac{1}{2} s_2^{hkl} [\sigma_{13} \cos \varphi + \sigma_{23} \sin \varphi] \sin 2\psi \dots\dots\dots <1>
 \end{aligned}$$

For the biaxial stress analysis ($\sigma_{33} = \tau_{13} = \tau_{23} = 0$ and $\varphi = 0$), the measurement result plots of $\varepsilon_{\varphi\psi}$ versus $\sin^2 \psi$ are shown predominantly on a certain direction.

$$\varepsilon = \frac{d_\psi - d_{\psi=0}}{d_{\psi=0}} = \frac{1+\nu}{E} \sigma \sin^2 \psi - \frac{\nu}{E} [\sigma_{11} + \sigma_{22}] \quad \sigma = \frac{\left(\frac{\partial \varepsilon}{\partial \sin^2 \psi} \right)}{\frac{1}{2} S_2} \dots\dots\dots \langle 2 \rangle$$

On the other hand, for the triaxial stress analysis, if shear stresses are present ($\tau_{13} \neq 0$ or $\tau_{23} \neq 0$) then the plot of $\varepsilon_{\phi\psi}$ versus $\sin^2 \psi$ is an ellipse, showing the so-called “ ψ – splitting ” for $\psi > 0$ and $\psi < 0$.

$$\varepsilon_{\phi\psi} = \frac{1}{2} S_2^{hkl} [\sigma_\phi - \sigma_{33}] \sin^2 \psi + \frac{1}{2} S_2^{hkl} \tau_\phi \sin 2\psi + \frac{1}{2} S_2^{hkl} \sigma_{33} - S_1^{hkl} \gamma(\sigma) \dots\dots\dots \langle 3 \rangle$$

where $\gamma(\sigma) = \sigma_{11} + \sigma_{22} + \sigma_{33}$ (3)

Table 3 shows the results of residual stresses measured by x-ray diffraction method on the hydroformed aluminium sheet, and Table 4 the results of principal stresses calculated from the results of Table 3. In general, for the residual stresses the negative sign means compressive stress, and the positive sign tensile stress. Therefore, it seems that the residual stresses on the sample are all compressive stresses except 7R area at $\phi=0^\circ$. Considering that $\phi=90^\circ$ shows larges compressive stress, there might be a large deformation occurred in that direction, and the amount of spring back after the forming process also could be large. It can be proved from the fact that the heights of the hydroformed profile are not as high as those of designed condition, and the radius of the profile is not same with that of designed (Table 1 and Table 2).

Table 3. The residual stresses (MPa) on the hydroformed aluminium sheet

	1R	2R	3R	4R	5R	6R	7R
$\phi=0^\circ$	-15.1	-18.1	-40.6	-25.5	-148.9	-44.7	31.9
$\phi=45^\circ$	-67.4	-66.4	-45.3	-32.2	-231.0	-64.4	-35.0
$\phi=90^\circ$	-102.3	-97.3	-102.8	-122.2	-331.8	-87.6	-60.5

*1mm of radius = 1R, 2mm of radius = 2R, ... 7mm of radius = 7R

Table 4. The principal stresses (MPa) and angles on the hydroformed aluminium sheet

	1R	2R	3R	4R	5R	6R	7R
σ_1	-16.4	-17.21	-30.88	-10.05	-148.42	-44.63	36.28
σ_2	-89.3	-98.27	-112.48	-137.64	-332.23	-87.71	-64.9
ϕ°	6	6	-20	-20	-2	-2	-77

In addition, as was mentioned above, since the plot of $\varepsilon_{\phi\psi}$ versus $\sin^2 \psi$ is an ellipse from the x-ray stress measurement results (Fig 8), shear stresses exist on the hydroformed aluminium sheet. Fig 8 shows the plot results of 4mm radius profile on 0° , 45° , and 90° .

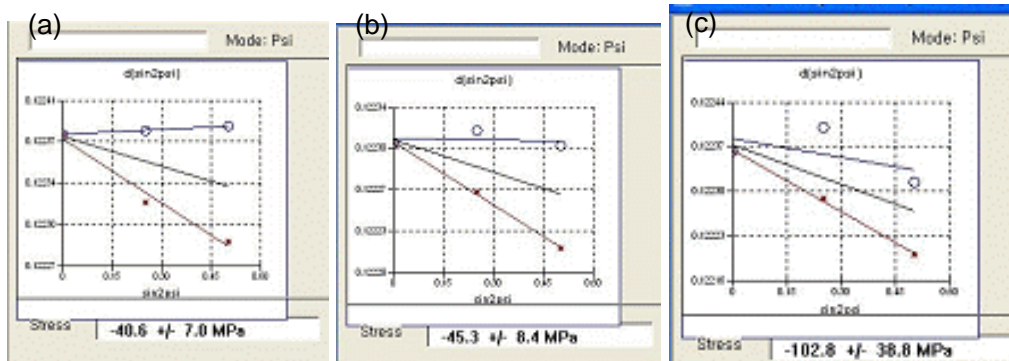


Figure 8. the plot results of 4mm radius profile on (a) 0°, (b) 45°, and (c) 90°.

3.3. FINITE ELEMENTAL ANALYSIS

Fig 9 shows the principal stress, σ_1 , of 2mm radius profile aluminium sheet from the simulation. Considering that σ_1 from the experiment was about -17 MPa, the maximum stress from the simulation was about -2MPa. In addition, σ_2 from the experiment was about -98MPa, while that was about -122MPa. Although there are some differences between the experiment and simulation, the residual stresses can roughly be predicted. The difference between them might be from the measurement error of x-ray which is caused by surface condition of the sample. Also, the materials properties for the simulation might not be precisely applied to those of materials which were used in the experiment.

Fig 10 also shows the principal stresses of 7mm radius profile aluminium sheet from the simulation. As similar with the results of 2mm radius profile, there was some difference between experiment and simulation results. However, for 7mm radius profile sample, tensile residual stress were observed for the maximum principal stress, and it could be expected that the sheet completely formed along the profile of die, and it may cause the tensile stress on the material.

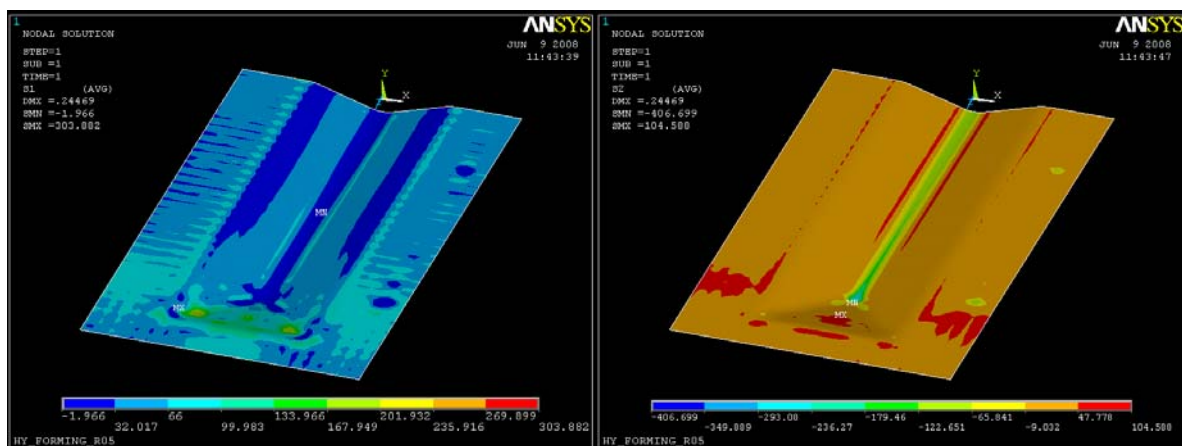


Figure 9. (a) Principal stress(σ_1) of Al 2mm radius profile, (b) Principal stress(σ_2) of Al 2mm radius profile sheet

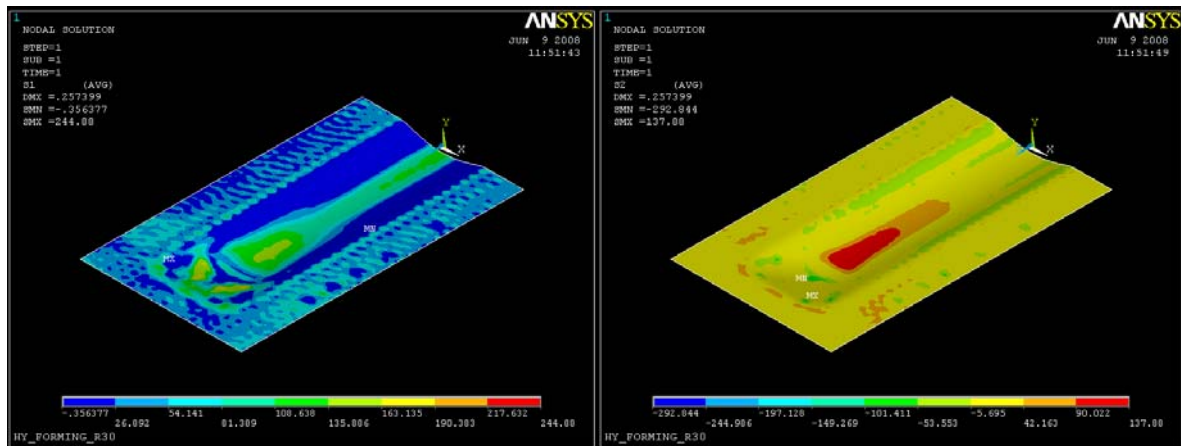


Figure 10. (a) Principal stress(σ_1) of Al 7mm radius profile, (b) Principal stress(σ_2) of Al 7mm radius profile sheet

4. CONCLUSIONS

The profile radius and height of aluminium sheet after hydroforming process was not same with that of designed shape. Thus, 450MPa was not enough to form the 1mm-6mm radius profile, and higher capacity of hydroforming press system is needed to increase the input pressure.

The residual stresses developed after hydroforming process were generally compressive stresses. The spring back phenomenon and not fully formed aluminium might be the cause of the results. The simulation roughly predicted the principal residual stresses

5. REFERENCES

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