Experimental Investigation of Novel Impact Hydroforming Technology on Sheet Metal Formability

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Abstract. The present article aims at investigating the effect of impact hydroforming (high strain rate forming) on the formability of AA5A06. In comparison, traditional hydroforming is also conducted. The formability of AA5A06 is investigated through hydro-bulge test at room temperature and strain rate range 4.67×10⁻³-3.18×10³ s⁻¹. The results show that the effective fracture equal-biaxial strain was not increased monotonically by increasing the impact velocity. There exists an optimal impact velocity, under which velocity the maximum effective fracture strain of biaxial zone increases by 62.18% compared with the quasi-static condition. It is concluded that impact hydroforming is an effective forming technology to achieve high formability and to form complex parts with low plasticity metals. In this paper the equi-biaxial strain of FLC is also theoretically calculated by Swift and M-K models. The plastic anisotropy is also taken into account during this calculation by introducing the anisotropy yield criteria, which is seldom discussed in the dynamic field. The results show that the M-K model is more suitable for calculating equi-biaxial strain of AA5A06 at high strain rate.

1. Introduction

Due to the poor formability of lightweight materials such as Al and Mg alloys, most forming technologies are not so suitable for them¹, especially at room temperature. Accordingly, advanced forming techniques are required to enhance their formability. Hydroforming is one of forming technologies used to improve the formability of lightweight materials². However, it still cannot fulfill the requirements of manufacturing in formability and for forming complex components³. Recently, a novel forming technology named impact hydroforming technology (IHF) is developed to overcome the limitations of traditional hydroforming and can achieve high formability and form complex components to fulfill the characteristics of the products.

Many researchers have investigated the hydro-bulge formability of aluminium sheet under varied strain rates. Grolleau⁴ developed dynamic bulge tests on 6111-T4 Al alloy sheets by using viscoelastic nylon bars in Split Hopkinson Pressure Bar (SHPB) tests. The strain rate reached up to 500 s⁻¹. The equivalent strain of aluminium 6111-T4 sheets was calculated by the strain signals. Ramezani⁵ further modified this method by changing the fluid to rubber. It is found that the strain of
AA6005-T6 increased with the strain rate (impact velocity) increasing according to the signals. The multi-axial strain of thin 3003 Al-Mn sheet under strain rate range of 200-850 s\(^{-1}\) was investigated by Justusson\(^{[6]}\) by developing a shock tube setup. The results demonstrate that this alloy shows remarkable ductility and plasticity at high strain rates. Indeed, the dynamic responses of the sheet or plate subjected to impulsive loading under water have been already investigated by many researchers in the dynamic field, such as the fluid-structure interactions (FSI)\(^{[7]}\) and underwater explosion\(^{[8, 9]}\). Blast energy absorption characteristic of structures is mainly focused in most of the investigations, and sandwich plates with foam layer are widely used.

Different from previous researches in dynamic domain, impulsive loading under water was taken as a forming technology in this paper, and the dynamic formability of sheet subjected to IHF is mainly discussed. The high strain rate (HSR) hydro-bulge test of the aluminum 5A06 sheet is investigated with different impact velocity in current study. Biaxial strain is obtained under HSR condition and the results are compared with the results of the quasi-static (QS) bulge. Then theoretically calculation is carried out for equi-biaxial strain of FLC by two FLC theories. Split Hopkinson Tensile Bar tests are implemented and HSR stress strain curves are obtained which will be used for the calculation of the HSR equi-biaxial strain. Plastic anisotropy is also taken into account during this calculation by introducing the anisotropy yield criteria, which was seldom introduced in HSR condition. The goal of this paper is to determine which FLC theory is able to predict the HSR formability more accurately, and the result can be a guide to estimate if a part can be formed successfully under IHF.

2. Experiment procedure

2.1. Material

The material used in this investigation is 1mm thickness AA5A06-O (Al-Mg alloy) sheet. The chemical compositions of AA5A06 are depicted in Table 1.

| Element | Al   | Mg   | Mn   | Fe   | Si   | Ti   | Zn   | Cu   | Be   |
|---------|------|------|------|------|------|------|------|------|------|
| Percent | 92.58| 6.50 | 0.54 | 0.16 | 0.06 | 0.06 | <0.05| <0.05| 0.0005|

2.2. The bulge experiment under QS and HSR conditions

The specimens are 160 mm diameter circle sheet for the QS bulge experiments. The specimens used in HRS are square blanks, there are 6 holes with 12 mm diameter evenly distributed at the 130mm diameter circle. There are series of 2.5 mm diameter circles etched by the electrochemical method onto the sheet before testing, and these circles are used to calculate the strain. All along forming, the grids were deformed and their circular shapes changed into ellipses with the minor and major axes characterizing the directions of principal strains. The values of these principal strains at failure can be acquired through calculating the minor and major axes of the ellipses close to the fracture site and matching them with the initial diameter of the grids.

QS bulge test was accomplished according to the ISO 12004-2\(^{[10]}\). The design of HSR testing system is depicted in Fig. 1, which is based on the principle of impact hydroforming. The projectile was fired out by the high pressure of the light gas gun, the projectile flew at high speed. The high-speed camera No. 1 Photron FASTCAM SA5 was used to calculate the impact velocity with 60000fps and 512×224 pixels resolution. Then the projectile impacted on the piston. The high pressure of water was produced by the impact of the projectile and piston together, and the sheet was deformed under this high pressure, as the process duration is very short, so the strain rate of the sheet was very high. The high-speed camera No. 2 Photron FASTCAM SA-X2 was used to record the bulging time with 100000fps and 192×256 pixels resolution. This testing system can get different strain rates by adjusting the firing pressure of light gas gun. The projectile was made from steel plate sticking to the plastic seat behind it. The weights of the projectile and the piston are 217g and 282g, respectively.
The experiments were repeated 3 times for each experimental condition. The QS experiments were taken by a hydraulic pump, and the HSR bulge tests were taken under release pressure of 0.3MPa, 0.4MPa, 0.5MPa, 1MPa and 2MPa of the light gas gun.

![HSR bulge testing system.](image1)

**Figure 1.** HSR bulge testing system.

The impact velocity of the projectile is calculated with the assistance of the high speed camera (No. 1). The calculated velocity results are shown in Table 2.

| Pressure (MPa) | 0.3     | 0.4     | 0.5     | 1.0     | 2.0     |
|---------------|---------|---------|---------|---------|---------|
| Impact velocity (m/s) | 103.92  | 121.48  | 134.16  | 189.74  | 268.33  |

![Table 2. Projectile velocity.](image2)

The equal biaxial crack strain was measured by the commercial sheet metal forming tester BCS-50BR. Due to off-line measurement, only the strain near to the crack can be detected, so the strain may deviate a little from the absolute equal biaxial path.

There are 2 selected principles needed to be fulfilled, both of the major and minor strain of circle \(i\) should be larger than the corresponding strain of circle \(j\), and the strain of the circle \(i\) should be closer to the equal biaxial line than circle \(j\) which is described as Eq. (1).

\[
\begin{align*}
\epsilon_1^i & > \epsilon_1^j, \epsilon_2^i & > \epsilon_2^j \\
|\epsilon_1^i - \epsilon_2^i| & < |\epsilon_1^j - \epsilon_2^j|
\end{align*}
\]

The forming time (\(t\)) of the QS bulge test is about 60 seconds. The forming time of the HSR bulge test is calculated with the assistance of the fast speed camera No. 2.

The effective strain rate (\(\dot{\varepsilon}\)) was defined as the effective strain divided by the forming time as described in Eq. (2), and it can be used to compare the changing between QS and HSR condition.

\[
\dot{\varepsilon} = \frac{\varepsilon}{t}
\]

2.3. The tensile test process under QS and HSR conditions

For the QS condition, the stress strain curves were obtained by a 100 kN Instron 5980 tensile tester. The dimension of the QS tensile specimens followed Chinese Standard GB/T 228.2-2015, the gauge length is 20mm.

The HSR tensile tests were accomplished by Split Hopkinson Tensile Bar (SHTB)\(^{[11]}\) as shown in Fig. 2 at room temperature. The geometrical details of the tensile specimens used in HSR tensile test are shown in Fig 3.

![Figure 2. The schematic of Split Hopkinson Tensile Bar.](image3)

![Figure 3. HSR specimen.](image4)
3. Theoretical algorithm of calculating the equi-biaxial strain

Several theoretical models have been developed for the calculation of FLC. The first ones were proposed by Swift [12] and Hill [13] assuming homogeneous sheet metals. Hora [14] developed Modified Maximum Force Criterion (MMFC) by modifying the Swift model. The FLC computed on the basis of the Hill’s model does not depend on the yield criterion, but only on the value of the hardening coefficient and only can be used to the negative range of the FLD. Marciniak and Kuczynski [15] proposed a model taking into account that sheet metals are non-homogeneous from both the geometrical and the structural point of view, which usually is briefly denominated as M–K model.

The research will investigate the theoretical prediction of Swift and M-K models both under QS and HSR conditions, and then will compare the calculated values with experiment results.

The calculation of the FLC considers the yield criteria and the hardening law. The Johnson-Cook hardening law is used by considering the strain rate effect. The stress strain curves were depicted in Fig. 4, and the HSR one fluctuate a little due to they are calculated from the stress waves signals. The strain rate of the QS condition is $10^{-3}$ s$^{-1}$, and the strain rate is around 2500 s$^{-1}$ of HSR condition according to the average effective strain rate of the sheet under HSR bulge experiment.

![Stress strain curves of AA5A06 under QS and HSR](image)

**Figure 4.** Stress strain curves of AA5A06 under QS and HSR

As the aluminum sheet has obvious anisotropic phenomena, the Hill48 anisotropic yield criteria [16] is chosen for the calculation. Anisotropic coefficients are calculated according to Kim [17] from tensile samples by measuring the deformation of etched circles with 1mm (QS) and 0.5 mm (HSR) initial diameter in the two principal directions. And the RD anisotropic coefficients are 0.563 and 0.865 under QS and HSR condition, respectively, the TD ones are 0.304 and 0.491 under the two conditions.

The swift theory is calculated according to [18]. The M-K theory is calculated according to [19], and only the biaxial part is selected and programmed by MATLAB, the flowchart is shown in Fig. 5. The initial thickness ratio was set to 0.998, and the increment of the major principal strain of perfect zone A was set to $1 \times 10^{-6}$.

![Matlab flowchart of M-K model](image)

**Figure 5.** Matlab flowchart of M-K model
4. Results and discussion

All the specimens were fractured under QS condition. Only the 0.3 MPa ones are not fractured under HSR conditions. The major and minor fracture strains of the biaxial grids of the specimens are plotted in Fig. 6. Only one data point is selected for each specimen according to Eq. (1). The blank square represents QS condition, and the solid mark represents HSR condition. The values of data points for the highest impact velocity are similar to the QS ones. The data points of the lowest impact velocity are positioned lowest because they are not fractured, which proves that there is a minimum velocity request for the impact loading for cracking the specimen. The position of other data points is located higher than the QS ones, but the strains are not increased monotonically with the impact velocity increasing. The results is similar to the research of Rohatgi [20]. The data points positioned highest under the 121.48 m/s impact velocity, and the increment is 62.18%, so there is an optimal impact velocity to get the maximum equal-biaxial strain.

On the whole, the forming time under HSR condition is decreased with the impact velocity increasing, and the range is 100-250µs. According to Eq. (2), the effective strain rate of the QS condition is 4.67×10⁻³ s⁻¹, the non-crack HSR one is 608 s⁻¹, and the effective strain rate of other HSR conditions is ranged 2.33×10⁻³-3.18×10⁻³ s⁻¹. And the strain rate variation is not very obvious of crack ones under HSR condition.

5. Conclusions

The investigation of the current study proves that the impact hydroforming can potentially improve the formability of aluminum sheet at room temperature.

The improvement of the effective strain under HSR condition compared with the QS condition is not monotonically increased with the impact velocity increasing. There exists an optimal impact speed. The maximum improvement of the effective strain was 62.18% with 121.48 m/s impact speed compared with the QS condition. The effective strain rate of HSR conditions is ranged 2.33×10⁻³-3.18×10⁻³ s⁻¹.

The theoretical calculated results of the equi-biaxial strain of swift model are opposite to the experimental results. The M-K model is more suitable to calculate the equibiaxial strain of the impact bulge which is a representative of impact hydroforming.
Acknowledgments

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