Effect of novel impact hydroforming technology on the formability of Al alloys

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Abstract. Currently, Aluminium (Al) alloys are increasingly used in the aerospace and automobile industries because of their outstanding properties such as lightweight and corrosion resistance properties. On the other hand, the applications of these materials are limited due to their poor formability especially at room temperature. Although hydroforming technology is one of the technique used to improve the formability of Al alloys, it still cannot fulfil the requirements of designers and manufacturers to form thin-walled complex shaped components. It has been found that high-speed forming is able to improve the formability of lightweight metals at room temperature. Thus, this investigation aims at investigating the effect of the novel technology called impact hydroforming (high-strain-rate forming) on the formability of Al alloys. Impact hydroforming (IHF) technology is proposed by combining the advantages of high-speed forming and hydroforming, and it was used to address the issues of quasi-static hydroforming. A high strain rate uniaxial tensile test was accomplished using Hopkinson tensile bar to investigate the effect of high strain rate on the formability of Al alloys. Thereafter, an IHF bulge experiment setup was developed by making use of a light gas gun which can accelerate the projectile up to 300m/s. The results show that the ductility and the formability of the Al alloy increased under high strain rate conditions, which means that the high-speed forming which is the basics of IHF technology is an appropriate method to improve the formability of Al alloys and form complex shape components.

1. Introduction

The pursuit of lightweight component designs is driving current interest in manufacturing complex parts in materials that are difficult to form such as Al alloys [1-3]. Innovative forming processes are required to meet these challenges and impulse forming technologies are able to fulfil some of these requirements [4, 5]. The impulse forming processes include electromagnetic forming (EMF) [6], fluid pressure forming such as electro-hydraulic forming (EHF) [7] and explosive forming, and novel approaches such as laser shock forming. However, to date, these technologies have not been widely implemented in mass production. This article is devoted to develop a kind of impulse forming process and equipment that can be applied industrially which is called impact hydroforming (IHF). IHF technology originated in the 1960s [8]. It was called pneumo- mechanical principle for the first known prototype machine developed by Bruno [9] in 1968 and Tominga and Takamatsu [10] in 1969. Kosing presented a further development of this principle and named it high speed metal forming [11]. It was also translated to high velocity hydroforming by Khodko et al. [12]. Nowadays, it is called impact hydroforming by Lang et al. [13] and Wang et al. [14]. IHF is performed by the high-pressure pulse, which is created by an impact of a flying projectile on an enclosed volume of a liquid that fills the working chamber of a press. The process is characterized by a short forming time, 100–500 ms, and the strain rate can reach $10^3$–$10^4$ s⁻¹. The
technology has a number of special features that makes it different from other forming technologies, such as reduce springback, no need of sealing, high quality of the part surface, filling ability for small geometric features and increasing the formability of low plasticity alloys. Therefore IHF is possible to solve the problem that the formability of aluminium alloy sheets is not sufficient to form a product with complicated configurations under traditional hydroforming (HF) process at room temperature [15, 16]. Many researchers have investigated the formability of aluminium alloy sheets under different strain rates according impulse principle. Grolleau et al. [17] performed dynamic bulge tests on 6111-T4Al alloy sheets by using Split Hopkinson Pressure Bar (SHPB) with viscoelastic nylon bars. The strain rate reached up to 500 s⁻¹. Ramezani and Ripin [18] further refined this method by changing the fluid to rubber. It can be seen that the strain of the AA6005-T6 increased according to the signals with the strain rate (impact velocity) increasing. Justusson et al. [19] investigated the response of multi-axial strain of thin 3003 Al–Mn sheets under strain rate range of 200–850 s⁻¹ by developing a shock tube setup. The alloy showed remarkable ductility and plasticity at high strain rates. It is of significance to apply IHF to practical production only when the high strain rate (HSR) formability of 5A06 increase compared with the formability of quasi-static (QS) HF. The dynamic formability of 5A06 aluminium sheet subjected to HSR liquid impulse loading is investigated. An HSR bulge experiment setup was developed, and HSR bulge tests of 5A06 sheets were implemented with different impact velocity. The thickness strain representing the thinning ability was obtained and the results were compared with those of the QS bulge tests.

This study aims at proposing a feasible solution for industry application. An advanced IHF equipment with excellent working parameters was designed and manufactured according to IHF principle. The impact velocity ranges from 10 to 80 m/s, the impact energy can reach as high as 200 kJ. Finally the IHF equipment was used to form a qualified double frames high drawing ratio (DR) aluminium aircraft sheet parts with complicated shape and small fillets which cannot be formed with traditional press forming and HF.

2. Experimental Material and procedures

2.1. Material description

The material used in this investigation was Al-Mg 5A06-O alloy sheets. The chemical compositions and microstructure of AA5A06-O before testing were depicted in Table 1 and Figure 1.

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

Figure 1. Microstructure of as received 5A06-O sheet.

2.2. QS and HSR tensile experiments

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 20 mm.
The HSR tensile tests were accomplished by Split Hopkinson Tensile Bar (SHTB) as shown in Figs. 2. The geometrical details of the tensile specimens used in HSR tensile test and the actual setup of SHTB are depicted in Figs. 3 and 4. The Engineering stress-strain curves obtained from QS and HSR tensile experiments is shown in Fig. 5.

2.3. The bulge experiment under QS and HSR conditions
A series of 2.5 mm diameter circles were etched onto the sheet before bulge test. The liquid cavity diameter is 65 mm both under QS and HSR conditions. The conventional bulge setup was used under QS condition. The HSR bulge testing system is depicted in Fig. 6, which is based on the IHF principle. The projectile flew at high speed after it was fired out by the high pressure of the light gas gun. 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. This testing system can get different strain rates by adjusting the firing pressure of the light gas gun. The projectile was made from steel plate which sticks to the plastic seat behind it. The weights of the projectile and the piston are 217 g and 282 g, respectively. The calculation of the projectile impact velocity is assisted with high-speed camera No. 1. The results are shown in Table 2.

| Pressure (MPa) | 0.3 | 0.4 | 0.5 | 1   | 2   |
|----------------|-----|-----|-----|-----|-----|
| Impact velocity (m/s) | 103.92 | 121.48 | 134.16 | 189.74 | 268.33 |

The major and minor strains were measured after the experiments and there are 4 indexes used to compare the formability between QS and HSR bugle tests. The thickness strain $\varepsilon_3$ is calculated by Eq. 1

$$\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0$$  \hfill (1)
The improvement of the thickness strain $\Delta \varepsilon_3\%$ of HSR bugle test compared with the QS condition was defined by Eq. 2.

$$\Delta \varepsilon_3\% = \frac{\varepsilon_3^{\text{HSR}} - \varepsilon_3^{\text{QS}}}{\varepsilon_3^{\text{QS}}} \times 100\%$$ (2)

Effective fracture strain $\bar{\varepsilon}$ was calculated according to Eq. 3.

$$\bar{\varepsilon} = \frac{1}{3} \sqrt{2[(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2]}$$ (3)

The effective strain rate $\dot{\varepsilon}$ was defined as the effective strain divided by the forming time as described in Eq. (4).

$$\dot{\varepsilon} = \frac{\bar{\varepsilon}}{t}$$ (4)

The forming time $t$ of the QS condition is about 60 seconds. The forming time of the HSR bulge tests is calculated according to the number of images captured by the high speed camera No. 2.

Figure 6. The schematic of HSR bulge test setup.

3. Results and Discussion

3.1. Dynamic behavior and formability of AA5A06-T8 sheets

The QS stress-strain curves are shown in Fig. 5. The elongation increased more than 40% under HSR condition compared with QS condition for uniaxial state. All the specimens were cracked in the bulge tests under QS and HSR conditions except the 0.3 MPa ones. The major and minor strains of the circles of the specimens after cracking are plotted in Fig. 7. The blank squares represent the QS condition. The position of data points of the highest impact velocity is similar to the QS ones. The data points of the lowest impact velocity are positioned lowest because they are not cracked. This proves that there is a minimum impact velocity request. The position of other data points are located higher than the QS ones, but the strains are not increased monotonically with the impact velocity increasing, the data points are positioned highest under the 121.48 m/s impact velocity, hence there is an optimal impact velocity to get the maximum major and minor strain. The optimal impact velocity exists is related to the crack mode of specimens as shown in Fig. 8. The deformation mode at lower impact velocity (103.92 m/s) is the same as that of QS bulge, and the specimen was not cracked, the deformation is not sufficient. The deformation is further concentrated on the apex and very tiny crack happened at the apex with the velocity increasing (121.48 m/s), and this is the optimal impact velocity. The specimen was cracked to two half by continuously increasing the impact velocity (131.46 m/s). The specimen was cracked to three petals at even higher impact velocities (189.74 m/s and 268.33 m/s), the deformation is more evenly distributed to the whole specimen but not concentrated on the apex. The $\varepsilon_2$ and the $\Delta \varepsilon_3\%$ of HSR bulge compared with that of QS tests are shown in Fig. 9. The impact velocity of QS condition is treated as 0 m/s. All of the $\varepsilon_3$ of IHF increased than that of QS condition except the un-cracked ones. According to Eq. (1), the $\varepsilon_3$ is equal to $- (\varepsilon_1 + \varepsilon_2)$, therefore the optimal impact velocity for getting maximum $\Delta \varepsilon_3\%$ is the same with the optimal impact velocity for getting the maximum major and minor strains, and the maximum $\Delta \varepsilon_3\%$ is 62.06% under 121.48 m/s impact velocity. The bulge test setup also used to obtain the FLC of 5A06 which is depicted as Fig. 10. The result of this paper is basically the same with Maris research [16] of AA5182-O, but there are some differences. The
increase is equal for the whole FLC zone of Maris research, while in this paper, the increase of biaxial zone is nearly twice of the increase of the tension-compression zone.

**Figure 7.** Major and minor strains of specimens.

**Figure 8.** Specimens after bulge tests (m/s).

**Figure 9.** Thickness strain and thickness strain increase of specimens.

**Figure 10.** FLC of 5A06-O sheets under HF and IHF process.

3.2. Details of design and manufacture of IHF machine

The purpose of this study is to find a feasible solution to form lightweight materials which have poor formability at room temperature. Therefore the advanced IHF equipment was designed and manufactured according to the principle of IHF which is depicted as Fig. 11. There are four zones of this equipment. Power zone can provide very high acceleration to the projectile which is as high as 3200 m/s². Acceleration zone supplies the acceleration distance for the projectile and the release rig. The dynamic resistance reduction technology is implemented by controlling the air and adopting special structure for reaching high impact velocity. Forming zone supplies the liquid chamber, binder hydraulic cylinder and moveable working table. Control zone supplies the control function to all of the hydraulic valves to control the action of the equipment. And the equipment can run both under manual and automatic mode by inputting the code to the control board. The power source of the equipment of current research is hydraulic driven system, which is capable of providing higher forming energy. While for previous works, the power source is pneumatic or explosive material, and their projectile is a solid cylinder which can freely move in the acceleration tube. The projectile of the current equipment is connected and controlled by a driven rod, which is capable of realizing more precise control. Furthermore, this equipment is more automatically run, which is suitable for industrial application.

3.3. Aircraft sheet parts manufactured by HF and IHF

The complicated aircraft Al frame sheet part is shown as Fig. 12. There are concave 1 and 2, 8-shaped convex and outer surfaces of this part. The drawing ratio (DR) is defined by the square root of the ratio of the blank area and the concave area in this paper. The DR is 3.88 and 3.52 for concave 1 and 2 respectively. The DR is 2.61 if they are calculated together, even though the DR is much higher than the common DR limit of steel which is 2. Hence this part needs many steps redrawing to reduce the DR for each step. The convex zone between the two concave zones is very easy to crack due to both of the two concaves will compete the material of the convex zone during forming, and the strain is very easy
to exceed the forming limit curve (FLC). In addition, there are many 2 mm small fillets at the bottom of the concave and the outer surface, which further increases the difficulty of forming this part. The smaller is the radius, the higher is the pressure according to HF theory. The 2 mm radius and 1 mm thickness sheet, will need half of yield strength which is about 90 MPa. The material which has already contacted the die surface is difficult to flow and is difficult to supply material to the radius zone due to the friction under this high pressure. The strain of the radius material is already very near the FLC after the hydraulic deep drawing, and now only the radius material itself is able to stretch. The strain of the radius materials will exceed the FLC easily with increased pressure, the crack will happen. Nowadays it is commonly manufactured by dropping press technology in aircraft manufacture industry, which needs many steps and lots of manual assistance to eliminate wrinkling and control the material flow to prevent cracks as shown in Fig. 13. FE simulation of HF process was carried out to check the feasibility of IHF before implementing forming processes as shown in Fig. 14. According to the strain distribution demand by FE simulation analysis as shown in Fig. 15, the FLC of HF cannot fulfil the requirements, the FLC of IHF is more possible to fulfil the demand. Therefore IHF is more likely to solve the crack problem. One step IHF process was used to form this this part, however, the final part is also contains cracks and also According to the strain distribution demand by FE simulation analysis as depicted in Figs. 16 and 17, the FLC of one step IHF process cannot fulfil the requirements. Thus, two steps IHF process was used to address the aforementioned issue.

By using the two-step HF, there was also a crack at the corner of the adjacent zone of the two concaves, although the wrinkle was eliminated compared with drop forming as shown in Fig. 18. Afterwards, the two-step IHF experiment was carried out. The impulse per unit area of HSR bulge setup is 0.88–2.28 x 10⁴ Pa s. The impulse per unit area for forming the complicated frame part is set to 1.51–4.52 x 10⁴ Pa s which is nearly twice of that of the bulge test by considering the complex geometry effect. A qualified aircraft double-frame Al sheet part was formed by IHF equipment as shown in Fig. 19. The concave 1

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**Figure 11.** The IHF machine  
**Figure 12.** The model of Al aircraft frame sheet  
**Figure 13.** Sheet part with wrinkle and crack formed by dropping press.

**Figure 14.** FE simulation of HF process  
**Figure 15.** The strain distribution of HF simulation  
**Figure 16.** FE simulation of HF process  
**Figure 17.** The strain distribution of HF simulation
and 2 were formed by 3–5 times impact process by increasing the impact velocity from 20 m/s to 60 m/s gradually. The distribution of thickness strain on the A–A section of the formed part for both HF and IHF processes are shown in Fig. 20. On the whole, the thickness strain of concave 1 is much larger than that of concave 2 of HF part. The IHF part endured more thinning and the thinning ratio of the two concaves are closer than those of HF part. There is a crack of the small radius position of concave 1 near the middle convex of HF part, as the strain exceeds the FLC of QS condition, but the strain demand was fulfilled for the IHF process by the promoted FLC, which verified the simulation results.

4. Conclusion
The investigation of the current research proves that IHF can potentially improve the formability of low plasticity metals like aluminium sheet at room temperature.
- The maximum improvement of the thickness strain of HSR bulge experiment is 62.06% with 121.48 m/s impact velocity compared with that of the QS condition. The effective strain rates of HSR condition are ranged 2.33–3.18 x 10³ s⁻¹.
- The IHF equipment was designed and manufactured for industrial application, which owns excellent working parameters such as high impact energy and high capacity of big dimensions part.
- The complicated double-frame aircraft aluminium sheet part with very high drawing ratio and small fillets was successfully formed which cannot be formed by dropping press and hydroforming at room temperature.

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