Springback inhibition of Ti-6Al-4V sheet with impact hydroforming at room temperature

H Li¹,², Y Xu¹, S F Chen¹, H W Song¹ and S H Zhang¹,*

¹ Shi-changxu Innovation Center for Advanced Materials, Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, People’s Republic of China
² School of Materials Science and Engineering, University of Science and Technology of China, Shenyang 110016, People’s Republic of China

* shzhang@imr.ac.cn

Abstract. Springback is a tough issue in sheet forming, and always leads to dimensional inaccuracy of formed parts. Titanium alloy selected as desired light-weight alloy has been playing significant roles in aerospace industry because of its good comprehensive performance. Whereas, titanium alloy components manufactured always exhibit severe springback at room temperature, which greatly restrict their application. To explore the possibility of reducing springback, rectangular lath-shaped parts with Ti-6Al-4V alloy sheet were fabricated by impact hydroforming (IHF) with self-designed equipment. Consequently, much lower springback is obtained using IHF with high strain rate than that formed by conventional stretch-bending with low strain rate. Great efforts are paid to clarify the mechanism of springback restriction under IHF. Different from traditional forming methods, more complex and high-speed interaction behavior between liquid and Ti-6Al-4V alloy sheet occurs. It considerably increases the difficulty for analyzing the deformation process of sheet under IHF. Thus, a novel solid-liquid coupling numerical simulation technology for IHF was developed. To validate the simulation accuracy, experiments with different forming processes and parameters were performed. Given the combined analysis of experimental and simulation results, it is found that distinctive forming paths are introduced between stretch-bending and IHF. Specifically, the preferred deformation region of sheet transfers from middle region for conventional stretch-bending to end regions under IHF, which mainly attributes to the unique loading behavior of liquid at high strain rate.

1. Introduction

Springback in sheet metal forming has always been a widely concerned issue¹⁻³, and always cause inaccurate dimensions and assembly failure of formed light-weight alloy sheet components used in aviation industries (e.g. titanium alloys, magnesium alloys, aluminium alloys et al.). Among these light-weight alloys, titanium alloy sheet components always exhibit severe springback after forming in room temperature due to low elastic modulus and high strength of material⁴. Hence, it’s necessary to develop reasonable springback reduction methods to raise the forming accuracy of titanium alloy components.

Generally, springback reduction strategies can be summarized as the optimization of loading path⁵ and forming parameters⁶ during forming, tool surface compensation⁷ before forming, pressurization calibration⁸⁻¹⁰ after forming et al. For instance, Feng et al. discovered non-uniform normal force and tangential adhesion force under viscous medium forming (VMF) could promote the uniformity of
stress distribution on the whole sheet and reduce the bending moment of sheet, which would finally lead to the reduction of springback\[5\]. In addition, Odenberger et al. utilized hot forming to improve the geometric accuracy of Ti-6Al-4V double-curved aero engine components by controlling subsequent holding time and temperature\[11\]. Their work proved that hot forming was helpful to promote stress relaxation of deformed parts and reduce springback. Nevertheless, above forming methods would induce higher manufacturing cost and lower forming efficiency. In this regards, it is necessary to develop more reasonable forming methods to realize accurate forming of titanium alloy sheet components with high efficiency and low cost.

According to recent studies about high strain rate forming methods, high strain rate loading can promote springback reduction of light-weight alloy and high-strength steel sheet at room temperature, e.g. electromagnetic forming\[12\], electro-hydraulic forming\[13\], explosive forming\[14\], hydrodynamic forming\[15\]. Dou et al. focussed on the effect of forming speed on the springback after sheet metal bending processes. They found that springback amount of V-bending and stretch-bending would decrease as the forming speed increasing\[16\]. Golovashchenko et al. had a study on the springback behavior of DP600 and DP980 high-strength steel sheets. It was discovered that high strain rate loading with electromagnetic force could effectively eliminate the internal stress of deformed parts and reduce springback\[17\]. Although these research results can strongly prove that high strain rate loading will promote springback inhibition of metal sheet, the potential mechanism for springback reduction under dynamic forming (e.g. IHF) on springback has not been revealed yet.

To discover the mechanism of springback reduction, the deformation history of sheet blank is always necessary to be analyzed. Since it is hard to precisely capture the instantaneous deformation behaviors of metal sheet and forming medium during high strain rate forming, it is naturally necessary to develop corresponding numerical simulation technologies. According to literatures reported in recent years, the dynamic deformation history of sheet under high strain rate could be acquired by solid-liquid coupling simulation technologies. O. Khodko quantitatively described the pressure wave during free hydrodynamic forming of tubular blanks using LS-DYNA\[18\]. Zohoor et al. coupled Arbitrary Lagrangian Eulerian (ALE) and Smoothed Particle Hydrodynamics (SPH) methods to simulate electrohydraulic forming process of sheet metal components\[19\]. Chen et al. conducted numerical simulations for impact hydroforming of AA 2B06-O sheet by fluid structure interaction (FSI) method with LS-DYNA\[20\]. Hajializadeh et al. simulated the impulsive hydroforming process of Al6061-T6 tube with the Coupled Eulerian Lagrangian (CEL) method by Abaqus\[21\]. Above simulation strategies for dynamic loading all provide positive instructions to the simulation strategy for IHF in this work.

In this research, springback behaviors of rectangular Ti-6Al-4V alloy sheets under impact hydroforming (IHF) at room temperature were investigated. Dynamic deformation histories of sheets were obtained by created IHF simulation with CEL method. Especially, the high-speed interaction behaviors between liquid and sheet blank under different strain rate were also analyzed in this work.

2. Experimental procedures

In this work, a rectangular thin-walled part is selected to test the springback behaviors of Ti-6Al-4V sheets under impact hydroforming (IHF). Experiments were conducted by self-designed IHF equipment and forming tools. The working principle of IHF can be described as that sheet blanks are deformed to the objective dimensions with provided tremendous kinetic energy of high-speed water at room temperature (Figure 1a). To contrast the deformation and springback behaviors of Ti-6Al-4V sheets under different forming velocities, experiments for IHF with different initial impact velocities (43m/s and 65m/s) and stretch-bending (0.1m/s) were performed relying on self-designed equipment and forming tools. Different from the liquid chamber with hollow structure for IHF, the dimension and geometric of the rigid punch for stretch-bending is manufactured to match that of the lower die (Figure 1b). To provide enough impact energy to make titanium alloy sheets to deform, the power source of projectile is derived from air compressor with high-power. The necessary dimensions of sheet blank and forming tools are listed in Table 1.
3. Simulation procedures for forming processes and springback behavior

Considering that it is almost impossible to precisely capture the deformation history of sheets during impact hydroforming, a solid-liquid coupling simulation method for IHF was developed by ABAQUS. To increase computation efficiency, the geometric of liquid chamber for IHF was simplified as rectangular column shape. In addition, rigid shell was selected as the element type of the forming tools (e.g. the rigid punch, the liquid chamber, the lower die and the projectile). To avoid over mesh distortion of high-speed water during IHF, the element type of water was defined as Eulerian element. Besides, the geometric of stretch-bending was modeled referring to factual dimensions, and shell element was utilized in all components in the created model. The established finite element models are shown in Figure 2. In order to accurately reflect dynamic deformation behaviors of Ti-6Al-4V alloy sheets under high strain rates, the simplified Johnson-Cook constitutive model (Equation 1) was utilized for defining material properties of Ti-6Al-4V sheet. Parameters of the constitutive model were referred to the computation value (Table 2) obtained by Hopkinson tensile tests in literature [22]. Furthermore, applied computation algorithm for forming processes relied on dynamic explicit algorithm (deformation process of sheets) and static implicit algorithm (prediction of springback), respectively. The initial velocities of the projectile and the moving speed of the rigid punch were all kept consistent with the experimental values. Other necessary simulation parameters were listed in Table 3.

\[
\sigma = (A + B\varepsilon^n)(1 + C\ln\varepsilon^s)
\]  

(1)
Figure 2. Geometric model for simulations (a) Stretch-bending (b) IHF

Table 2. The necessary simulation parameters in simulations.

| Friction coefficient | Contact type | The maximum size of mesh (mm) | The height of water column (mm) | Blank holder force (N) | Height of projectile (mm) |
|----------------------|--------------|------------------------------|--------------------------------|------------------------|--------------------------|
| 0.08                 | Self-contact | 3                            | 290                            | 0                      | 150                      |

Table 3. Parameters of the Johnson-Cook constitutive model of Ti-6Al-4V alloy[12].

| A (MPa) | B (MPa) | n   | C     |
|---------|---------|-----|-------|
| 1098    | 1092    | 0.93| 0.014 |

4. Results and discussion

Three rectangular thin-walled Ti-6Al-4V alloy parts under different forming conditions were obtained by simulations, the results of which shew great consistence to experimental results (Figure 3). It could be learned that severe positive springback of deformed sheet occurred after stretch-bending with 0.1 m/s. Differently, it was found that severe negative springback of deformed sheet occurs when the impact velocity rises up to 65 m/s under IHF. Specifically, little springback amount was obtained under the lower impact velocity of 43 m/s. Thus, it was discovered that severe springback of Ti-6Al-4V alloy sheets could be effectively reduced under IHF.
To explore the mechanism of the springback inhibition under IHF at room temperature, the interaction behaviors between sheet and forming medium were discussed during stretch-bending and IHF forming processes, as well as the variation histories of strain and stress. Considering that the interaction behaviors were always related to the geometric characteristics of forming medium, the flow behaviors of the working liquid during impact hydroforming were analyzed. Several representative frames of the deformed sheets during stretch-bending and the flow liquid during IHF were displayed in Figure 4. By comparison, it could be discovered that the deformation of sheets would be initial at the middle region and then transferred to the end regions during stretch-bending, which could be explained by the first contact interaction originating from the middle region of the sheets. On the contrary, the deformation of sheets began at the end regions and ended in the middle region during IHF, which was attributed to that the high-speed liquid would firstly flow onto the edges of the sheet under impact loading.
Change of sheet forming paths will lead to the variation of the stress and strain distributions. Obtained distributions of effective plastic strain under different impact velocities are shown in Figure 5(a). It can be seen that larger plastic strain occurs in the region of die fillet when applying over-high (65 m/s) or over-low level (0.1 m/s) forming velocities. In addition, the magnitude of plastic strain was obviously enhanced under IHF compared with that under stretch-bending (The maximum magnitude of effective plastic strain increased 0.1179 at the impact velocity of 65 m/s) in the middle region of sheets. Specifically, more uniform strain distribution was obtained at the impact velocity of 43 m/s. It illustrated that uniform distribution and increasing magnitude of plastic strain would promote the springback reduction of titanium alloy sheets. Additionally, distributions of von Mises stress along length direction of sheet obtained by simulations were shown in Figure 5(b). By computation, It was discovered that the average von Mises stress along length direction of sheet (x direction) obtained by IHF (237 MPa with the impact velocity of 43 m/s and 323 MPa with the impact velocity of 65 m/s) were much lower than that under stretch-bending (358MPa with the forming velocity of 0.1 m/s), which inferred that stress relief under IHF would lead to springback reduction.

Above all, the uniform distribution of plastic strain and the relief of residual stress under IHF will finally cause springback inhibition of Ti-6Al-4V alloy sheet at room temperature. Nevertheless, it was also discovered that the thickness reduction of obtained sheets along x direction were extremely restricted under IHF (Figure 6a). Similar variation law of thickness distributions of deformed sheets happens on the measured results (Figure 6b).
5. Conclusions
The springback behaviors of Ti-6Al-4V alloy sheets under IHF and stretch-bending were investigated by experiments and simulations. By comparing with the obtained results under stretch-bending and IHF, conclusions can be summarized as follows:

1. The preferred deformation region of sheet transfers from middle region for stretch-bending to end sides under IHF.
2. Stress relief and uniform distribution of plastic strain under IHF lead to the springback reduction of titanium alloy sheets at room temperature.
3. Thickness reduction of sheets will be restricted under IHF comparing with that under conventional stretch-bending.

References
[1] Badr O M, Rolfe B, Zhang P and Weiss M 2017 Int. J. Mech. Sci. 28-129 389-400.
[2] Orallo A, Trinidad J, Galdos L, Argandoña E S and Mendiguren J 2020 Aluminum Spring-back Reduction by Post-forming Electric Pulses. 23rd Int. Conf. on Material Forming 47 1387-1391.
[3] Liu G, Lin Z Q and Xu W L 2002 J. Mater. Process. Technol. 120 259-264.
[4] Zhao Y X, Peng L F and Lai X M 2018 Influence of the electric pulse on springback during stretch U-bending of Ti6Al4V titanium alloy sheets. J. Mater. Process. Technol. 261 12-23.
[5] Feng Y K, Shi S G, Wang Z Y and Wang Z J 2022 J. Mater. Process. Technol. 304 117548.
[6] Edwards W L, Grimm T J, Ragai I and Roth J T 2017 45th SME North American Manufacturing Research Conference 10 329-338.
[7] Zhang Q F, Cai Z Y, Zhang Y and Li M Z 2013 Mater. Design. 47 377-385.
[8] Cui X H, Du Z H, Xiao A, Yan Z Q, Qiu D Y, Yu H L and Chen B G 2021 J. Mater. Process. Technol. 288 116889.
[9] Du Z H, Yan Z Q, Cui X H, Chen B G, Yu H L, Qiu D Y, Xia W Z and Deng Z S 2022 J. Mater. Process. Technol. 299 117340.
[10] Xie H Y, Wang Q, Liu K, Peng F, Dong X H, Wang J F 2015 J. Mater. Process. Technol. 219 321-327.
[11] Odenberger E L, Pederson R, Oldenburg M 2019 Int. J. Adv. Manuf. Tech. 104 3439-3455.
[12] Lai Z P, Cao Q L, Zhang B, Han X T, Zhou Z Y, Xiong Q, Zhang X, Chen Q and Li L 2015 J. Mater. Process. Technol. 222 13-20.
[13] Lu X and Hong J 2018 17th Int. Conf. on Metal Forming, Metal Forming 15 (Toyohashi: Japan Elsevier) p 907-914.
[14] Tong Z, Li Z, Cheng B and Zhang R 2008 J. Mater. Process. Technol. 203 449-453.
[15] Ma Y, Chen S F, Chen D Y, Banabic D, Song H W, Xu Y, Zhang S H, Fan X S and Wang Q 2021 Int. J. Mater. Form. 14 1221-1232.
[16] Dou L Y, Li X Q, Dong H R, Li D S and Peng X Y 2020 Int. Deep-Drawing Research Group, Materials Science and Engineering 967 (Seoul, South Korea IOP) p 012065.
[17] Golovashchenko S F, Gillard A J, Mamutov A V and Ibrahim R 2014 J. Mater. Process. Technol. 214 2796-2810.
[18] Khodko O, Zaytsev V, Sukaylo V, Verezub N and Scicluna S 2015 J. Manuf. Process. 20 304-313.
[19] Zohoor M and Mousavi S M 2018 J. Manuf. Process. 20 16-28.
[20] Chen D Y, Zhang S H, Xu Y, Ma Y, Song H W and Xia L L 2020 Int. Deep-Drawing Research Group, Materials Science and Engineering 967 (Seoul, South Korea IOP) p 012028.
[21] Hajializadeh F and Mashhadi M M 2015 J. Manuf. Process. 20 257-273.
[22] Lesuer D 2000 Aluminium FAA Technical Report. 1-30.