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Investigating Spring Back Characteristic of Construction Domain Aluminium Alloy Sheets upon Subjected to Stamping

Vanda Trivana[1*] **and Gerry Gerald Alexander**[2]

[1]*College of Civil Engineering, Tongji University, Shanghai, 200092, China*

[2]*Department of Hydraulic and Ocean Engineering, National Cheng Kung University, Tainan, 70101, Taiwan*

Abstract

Nowadays, aluminum alloy is widely used in spatial structures, and aluminum alloy gusset joint is also the most widely used connection method in spatial structure. With the improvement of the requirements of architectural design effect, aluminum alloy structure is becoming one of the forms of special-shaped space. Combined with the shape structure of curved reticulated shell, its gusset plate is usually made of arc plate formed by stamping. However, due to its low elastic modulus, poor plastic deformation ability at room temperature and uneven distribution of stress and strain, the metal sheet begins to spring back after the stamping load is unloaded. At present, the main spring back control methods for aluminum alloy plate are laser peen forming, cold stamping forming and multi- point forming. There are three kinds of spring back prediction methods for sheet metal forming: analytical method, finite element method and experimental method. Spring back is one of the most prominent and complicated problems during the processing and formation of the aluminum alloy sheet. The final shape of the curved panel is also dependent on the spring back after formation. When the spring back exceeds the allowable error, it will directly affect the appearance of the component, and therefore, the overall assembly. Ultimately, the bearing performance will further affect the safety protocols involved in respective components.

Keywords: Aluminum alloy sheet; Spatial structures; Curved reticulated shell; Stamping forming; Spring back

Introduction

Application of aluminum alloy in building structures

Owning to its light weight, high strength, strong plasticity, low maintenance cost, and good corrosion resistance, aluminum alloy materials have become a new type of construction material that promotes sustainable development in various domains. As a structural material, aluminum alloy has been widely used in aviation, machinery, shipbuilding, aerospace, automobile manufacturing and other fields [1]

The application of aluminum alloy in building structure can be traced back to the 1930's, and it is also mainly used in bridge structure. Currently, it is more widely used in transportation, construction, machinery and manufacturing. In the developmental process of the construction field, aluminum alloy has gradually demonstrated its advantages in combination with large-span spatial structures. The development of aluminum alloy spatial structures is later than that of steel grid structure and steel reticulated shell structure. The first aluminum alloy reticulated shell structure in the world was built in the United Kingdom, which is known as the dome of discovery [2] as shown in (Figure 1).

Figure 1: Dome of Discovery in England.

Since the 1950's, some European and American countries have used aluminum alloy as the load-bearing structure of buildings. After Mr. Fuller first proposed the concept of geodesic spherical dome in 1964, the application of aluminum alloy geodesic spherical dome in the United States has become more and more extensive, such as the Spruce Goose in Los Angeles built in the 1970's, as shown in (Figure 2).

Figure 2: Spruce Goose.

The Caspary Auditorium at Rockefeller University built in New York in 1957, with single-layer spherical reticulated shell, as shown in (Figure 3).

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*Corresponding Author: Vanda Trivana, College of Civil Engineering, Tongji University, Shanghai, 200092, China, E-mail: vandatrivana@tongji.edu.cn

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Figure 3: Caspary Auditorium.

In 1992, the Back River Wastewater Treatment Plant was built in Maryland of the United States, which is used for building anti-corrosion requirements, as shown in (Figure 4).

Figure 4: Back River Wastewater Treatment Plant.

Up to now, there are about 7000 aluminum alloy single-layer latticed shells in use in the United States. Aluminum alloy space grid structure can maintain good performance in humid environment, so it is increasingly widely used in the world. One of the most representatives is the first greenhouse of Niigata prefectural botanical garden built in Japan, which applied the single-layer spherical reticulated shell in 1998 as shown in (Figure 5).

Figure 5: Niigata Prefectural Botanical Garden.

Spatial structure is mainly divided into grid structure and reticulated shell structure. It is a spatial structure composed of roughly the same grid or smaller units, which can uniformly transfer forces in three directions. Japanese scholars Hiyama and Ishikawa [3-5] have done static finite element simulation of aluminum alloy double-layer grid, and proposed that the criterion of dynamic collapse failure of grid can be determined by the critical displacement of the joint between the roof and the substructure. In 1996, Sugizaki [6] and others adopted the scale test method to analyze four aluminum alloy single-layer spherical latticed shells with diameter of 4.2m. The test results show that the bearing capacity of the latticed shell with only concentrated load at the top is higher than that with only uniform load.

Stamping Method of Aluminum Alloy Plate

Laser peen forming

Laser forming uses laser to provide energy, forming objects and forming equipment can be formed without direct contact. The principle of laser bending forming is to irradiate the plate by laser source to heat the plate locally. The temperature difference in different areas of the material in the two processes of thermal expansion and cold contraction, heating and cooling results in different yield stress and elastic modulus and deformation. Laser forming can achieve repeated heating and cooling for many times to achieve the accumulation of deformation. It can be bent by changing the scanning path to obtain disc and spherical parts. Moreover, it can also be used for leveling sheet metal parts. [7,8]

Laser bending appeared in the 1980's. Namba Y [9] a Japanese scholar, proposed for the first time a method of plastic deformation of sheet metal without external force and only thermal stress, whose method is laser bending. Subsequently, many scholars have carried out more in-depth research on the forming mechanism of this technology. Edwardson and Magee of the University of Liverpool and Bao and Yao of Columbia University have carried out relevant experimental research on laser bending forming, and each has achieved certain results [10-12]. With the development of computer technology and the continuous upgrading of large commercial finite element software such as ANSYS and ABAQUS, great progress has been made in the numerical simulation of laser forming. Vollertsen et al. [13] established a finite difference model, which is mainly suitable for two-dimensional laser bending. Alberti [14] et al. established a finite element analysis model based on the mechanism of temperature gradient, focused on the influence of material yield stress related to temperature on plate deformation, and proposed a thermo mechanical coupling model. Furthermore, Hsiao et al. [15-20] have made in-depth research on the numerical simulation of laser forming. In addition to the experimental research and numerical simulation, the research on the microstructure and properties after laser scanning is also a research focus of laser bending forming Merklien [22,23] of the University of Erlangen-Nuremberg in Germany studied the change of material properties of pure aluminum and Al1050 alloys and Al6082 alloys after laser scanning.

Plastic Forming

At present, cold stamping is the most common method of aluminum alloy forming, which accounts for the largest proportion in industrial production, because stamping confers advantages including: low energy consumption, simple operation and high stamping efficiency [24-26].

However, due to the poor formability of medium and high strength aluminum alloy at room temperature, they are more prone to cracks, wrinkles and other defects during the stamping process. Therefore, in order to improve the formability of aluminum alloy in cold stamping, Golovashchenko and other scholars [27] developed a method of forming 6111-T4 aluminum alloy only by stamping and annealing. At the same time, a calculation process of stress based FLC was proposed. Residual effective plastic strain (REPS) was determined by overlapping stress. The conclusion was that stress based FLC and residual effective obtained, thereby resulting in the increase of 6111-T4 aluminum alloy elongation from 25% to 45%.

Warm stamping refers to the stamping process in which the forming temperature is higher than room temperature and the sheet is heated below the recrystallization temperature. Finch and Wilson [28,29] studied the warm stamping forming experiment of aluminum alloy sheet and established the relevant theories behind it. Before the bulging experiment, the sheet was heated, annealed and tempered respectively. Compared with the room temperature tests, the drawing limit of warm aluminum alloy tube is larger, which indicates that the forming temperature affects the malleability of aluminum alloy sheet. In addition, the drawing limit is also related to the blank holder force, mould design and other factors. The diagram of warm stamping forming is shown in (Figure 6).

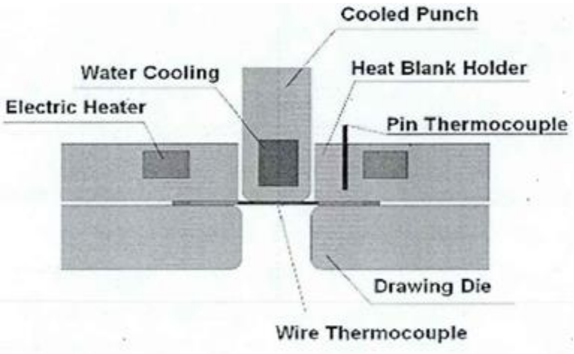

Figure 6: Warm Stamping.[28]

In the study of constitutive model of warm stamping of aluminum alloy, Bai [30] proposed the constitutive model of warm stamping of aluminum alloy AA5754 based on continuum damage mechanics, and theoretically deduced that the stamping speed is 20-300 MGS and the temperature range is 200-300°C. Finally, the experimental results are consistent with the theoretical derivation. Based on AA5754 aluminum alloy, Mohamed [31] studied the forming limit of warm forming.

Abedrabbo et al. [32-34]. University of Michigan, carried out warm forming experiments and numerical simulation for 5182, 5754, 5083 aluminum alloys. Alexandrov et al. [35] also simulated the warm forming process of aluminum alloy, and applied Zener-Hollomon criterion to the experiment.

By increasing the temperature, hot stamping of aluminum alloy can solve the problem of low malleability in forming complex parts. Garrett [36] and other scholars studied the solution treatment and applied that to quench 6 series of aluminum alloy plates, which in turn influenced the solution treatment and quenching speed on both tensile strength and grain structure of the formed parts.

Flexible forming of 3D Curved Surface

Multi-point forming is a widely used way of 3D surface flexible forming, which breaks the traditional mould stamping and adopts the forming technology without mould. Through a series of discrete and orderly lattice up and down, whose height can be adjusted arbitrarily. Furthermore, combined with the rapid adjustment of the required shape by computer, the parts with different shapes can be punched out on a set of equipment. In the 1950's, Japan first proposed the concept of multi-point forming, because at that time, Japan was in the period of economic recovery and began to vigorously promote the development of shipbuilding industry. However, due to the high cost and long cycle of curved 3D sheet metal parts made by traditional mould stamping, the production demand of hull outer plate was seriously restricted.

F. Nishioka [37] developed the universal press in the 1970's. Although it is unable to solve the problems of smoothness and spring back, and high manufacturing costs are involved, many new processes have since been developed through continuous innovation and improvement. MIT scholar David. E. Hardt et al. [38,39] developed the multi-point stretch forming technology for aircraft skin as shown in (Figure 7).

Figure 7: Multi-point forming experiment machine.[39]

When the clamp applies tensile stress to the sheet, the multi-point mould lifts the sheet to produce tensile-bending deformation. The additional tensile stress makes the sheet fully deformed, which can reduce the spring back and improve the forming accuracy. However, the clamping part of the clamp needs to be removed in order to reduce the material utilization.

Wang [40] proposed a new method of force displacement separate control forming with controlling displacement with upper mould and providing force with lower mould. The principle is shown in (Figure 8).

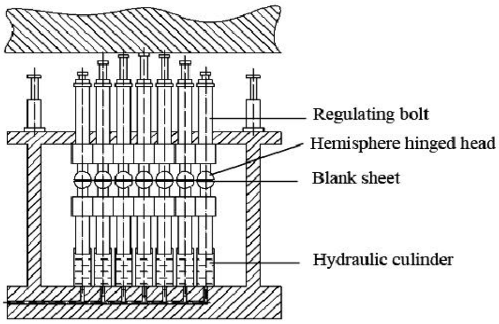

Figure 8: Force displacement controlled multi-point forming.[40]

The problem that the stroke of hydraulic cylinder is difficult to control is avoided by controlling the force and displacement separately. The sheet is always subjected to normal constraint in the forming process. Combining with hemispherical hinge indenter, the indentation and wrinkling can be restrained, and the additional tensile stress and repeated bending can be controlled. However, there are still some problems such as high manufacturing cost and difficult sealing of hydraulic cylinder. Peng [41] and others applied multi-point forming technology to polymer, and proposed the influence of the number and radius of punches on the precision of formed surface.

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Theoretical Study on Springback of Aluminum Alloy Sheet

At present, there are three kinds of spring back prediction methods for aluminum alloy sheet forming: analytical method, finite element method and experimental method.

Barrat and Lian [41] proposed a Barrat 89 yield criterion considering in-plane anisotropy, which can give a more accurate explanation for the yield behavior of sheet metal with structural anisotropy. Barlat 89 yield criterion takes into account the in-plane shear stress, which makes it more effective to simulate the rule of plastic flow behind the metal sheet during deep drawing process, therefore making it more reasonable to explain the yield behavior of material with strong texture, and comprehensively describes the influence of forming limit, in-plane anisotropy and yield function during sheet metal forming.

On the basis of Hill79 yield criterion and incremental theory, Zhang [43] proposed several strengthening models, and analyzed the stress distribution and spring back of the models in detail under different cyclic loading conditions. It is concluded that the selection of reinforcement model will affect the accuracy of calculation and results.

Yoshida and Uemori [44] established a double-sided material model by synthesizing the isotropic strengthening model and the kinematic hardening model, and proposed a mixed strengthening model, and named the model results after the author, namely Yoshida Uemori (Y-U) model. Chung and Lee [45] and other scholars considered the kinematic hardening rule and Bauschinger effect at the same time to study the aluminum alloy sheet by combining theory with experiment.

The second spring back prediction method is the finite element method. Lee SW [46] uses two different static implicit and explicit algorithms to simulate the spring back of S-beam parts of NUMISHEET'S96. Through comparative analysis, the accuracy of static implicit algorithm is higher than that of explicit algorithm. Xiongqi Peng [47] and other scholars selected two different models, Y-U kinematic strengthening model and isotropic strengthening model, to simulate the stamping and spring back of automobile high- strength steel structure using JSTAMP software. The results show that the prediction accuracy of Y-U model is higher than that of isotropic model.

S. Sumikawa [48] et al. considered the average young's modulus, plastic anisotropy, elastic anisotropy and Bauschinger effect, then established the constitutive model of the material, and used comparative analysis method to carry out the spring back test of several different steels, and concluded that the more accurate results can be obtained by considering the given material characteristics when simulating the spring back. Park [49] developed a new shell element for sheet metal stamping, and found that it can effectively improve the analysis speed.

Wang [50] of Imperial College London, based on AA5754 aluminum alloy, studied the spring back during hot stamping by combining numerical simulation with experiment. The results show that when the mould's temperature increases from 200°C to 4500°C, the reduction rate of spring back increases from 9.7% to 44.1% compared to that of cold stamping.

Aluminum Alloy Gusset Joints for Building

Aluminum alloy gusset joints are the patent developed by Temcor company of the United States, as shown in (Figure 9).

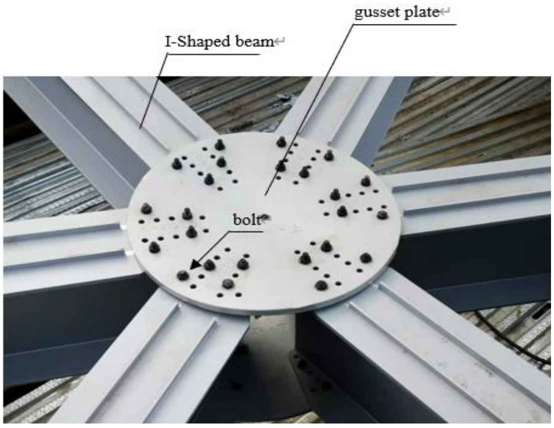


Figure 9: Temcor joint.

The traditional gusset joint form of plate joint is to connect the upper and lower flanges of six I-section members with an aluminum alloy cover plate at the center, and the upper and lower flanges of the members are connected with the aluminum alloy cover plate by fastening bolts.

Furthermore, a large number of studies have shown that aluminum alloy plate gusset is a typical semi-rigid joint [51]. The gusset plate is divided into plane plate joint and arc plate joint.

Large-span space aluminum alloy free-form surface reticulated shells have gradually been widely used in the construction field. The processing quality of the gusset plate is reflected in the important role of the overall assembly of the reticulated shell building model. It has always been one of the construction problems. Therefore, by accurately predicting the stamping of aluminum alloy gusset, the spring back rate of gusset plate will effectively ensure the quality of construction. In 2020, Guo [52] and other researchers have completed the first ellipsoidal aluminum alloy reticulated shell project in Ningbo, China, as shown in the figure below. There is no identical connection node, which implies that the curvature of the ellipsoidal reticulated shell with different heights and different plane positions, possess different camber, diameter, gusset plate hole positions, and rods' length and angle. Based on this, the calculation formula for the spring back of aluminum alloy arc panel joints, after taking into account of the opening area rate, the thickness of the joint plate followed by comparing it with the finite element model, justifies that the fitting equation can accurately predict the spring back rate.

However, this paper does not point out the influence of residual stress field on the mechanical performance of aluminum alloy arc gusset plate joints. After stamping, there is obvious stress concentration at the edge of the bolt hole of the gusset plate, and there are larger residual stresses in the remaining parts, which will affect the bearing performance of the gusset plate (Figure 10).

Figure 10: Ellipsoidal aluminum alloy reticulated shell project in Ningbo, China.

Liu et al. [52] carried out the finite element analysis of 500 single-layer aluminum alloy latticed shells, which influences material nonlinearity and initial defects on the stability bearing capacity of latticed shells.

According to the joint deformation mechanism, Xiong et al. [53] divided the moment-rotation curve of the joint obtained from the test into bolt initial fixation stage, bolt sliding stage, hole wall bearing stage and failure stage, which contributed to the proposal of the four-line model of the joint bending stiffness (Fig. 11), and resulted in the derivation of calculation formula for joint stiffness at each stage based on the component method and numerical simulation.

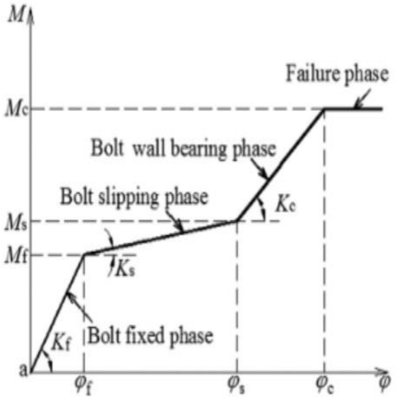
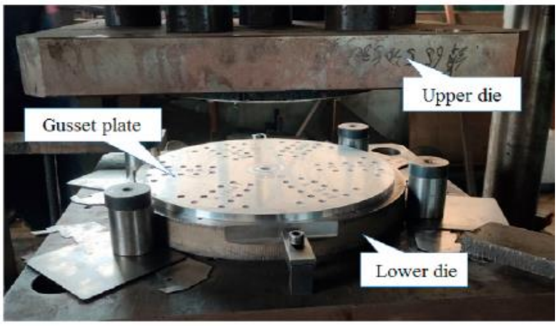
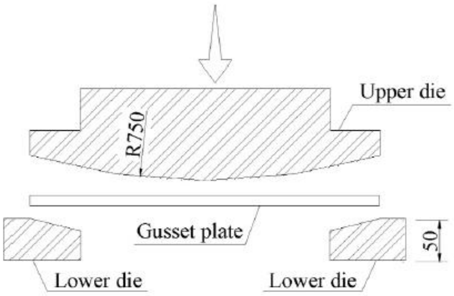


Figure 11: Four-line model.[54]

In 2020, Guo [55] and others derived the theoretical formula considering the material parameters and the thickness, width, radius and other parameters of the gusset plate based on the aluminum alloy gusset plate joint. The test is shown in the (figure 12).



(a) actual equipment



(b) schematic diagram

Figure 12: Stamping forming equipment.[55]

The 3D printing technology is introduced to measure the stamping amount of 9 aluminum alloy gusset plates with different parameters. Combined with ABAQUS finite element analysis, it is concluded that the spring back rate of the gusset plate increases correspondingly to the increase of radius, yield strength, while demonstrating an inversely proportional relationship as it decreases with the increase of stamping camber, thickness, elastic modulus, the area ratio of the bolt hole.

Conclusion

Aluminum alloy structure has become the development trend in many engineering fields because of its own characteristics. At the same time, the forming characteristics of aluminum sheet and steel sheet are not the same, especially the spring back defects of sheet after stamping, so the theoretical research of steel sheet forming cannot be completely integrated into aluminum sheet.

With the development of industry, the precision of products and parts is required to be higher. However, the plasticity of aluminum alloy plate at room temperature is lower than that of steel plate, which leads to greater spring back in the stamping process due to high yield strength and low elastic modulus. Spring back will make the size and shape error of parts larger, and the film adhesion is poor, which cannot meet the requirements of appearance design. This will greatly affect the assembly of aluminum alloy, and not to mention that aluminum sheet is also easily deformed during the forming process, hence implying that the stamping performance of aluminum alloy is lower than that of steel sheet.

After the termination of spring back, the elastic-plastic deformation and the elastic part stored in the deformation are released, but at the same time, it is limited by the adjacent plastic deformation area. Therefore, it is the uneven deformation that causes the residual stress in the plate. Residual stress is one of the important reasons leading to brittle fracture, stress corrosion, instability and fatigue fracture of components.

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