Research Article

Numerical Simulation and Experimental Research on Multi-Point Forming of Aluminum Alloy Sheets Based on Ultrasonic Vibration

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In this study, the multi-point plastic forming of 2024-O aluminum alloy sheets is the research object, ultrasonic vibration-assisted forming is applied in the stamping process, a combination of ABAQUS/EXPLICIT numerical simulation and theory is used, and multi-point forming experiments are performed to verify the research. In the process of multi-point forming, the influence of ultrasonic vibration on the plastic deformation and springback of sheet metal has inspired a new idea and method for multi-point forming of sheet metal. This paper presents the following: the basic theory of multi-point stamping and ultrasonic vibration-assisted metal sheet plastic forming; a comparison of the material parameters of the multi-point stamping method with and without ultrasonic vibration; the influence of different times on the results; the changes in parameters such as stress and strain at different frequencies; and the effect of its springback.

1. Introduction

Sheet metal forming processes are widely used to produce three-dimensional surfaces in many fields, including shipbuilding, aircraft manufacturing, vehicle bodies, and pressure vessel forming. Stamping is one of the most common sheet metal forming methods. For the conventional stamping process, which involves a matched solid die set, its advantages are short production time and high productivity. Nevertheless, large initial investments and a long setup time make its processes inflexible, only profitable for mass production, and economically unsuitable for single or small-batch products. Multi-point forming (MPF), which is a flexible manufacturing technique that consists of a set of adjustable base elements controlled by MPF-CAD/CAM software, was named by Li et al. [1, 2] and has been well developed in recent years. The basic principle is shown in Figure 1.

Multi-point forming originated and developed in Japan. This conception was first introduced in 1959. Nakajima [3] of the University of Tokyo, Japan, produced a simple multi-point forming experimental device—wire binding tool and designed a simple curved surface mould composed of wire bundles. He used a bundle of steel wires to form surfaces of different shapes according to the different axial positions of the steel wires and used the tool to form the sheet.

Kitano [4] successfully realized shell plate bending and forming tests using a universal adjustable press. Nishioka [5, 6] and others studied the process to form a hull shell, manufactured a multi-point press, and successfully pressed out 1 000 × 1 000 mm steel plates.

At the forefront, research was mainly represented by professor Li et al. [7] and Liu et al. [8] of Jilin University. They have conducted in-depth research on the theory and principles of multi-point forming. Liu et al. [9] proposed a method to predict the springback of the double-curved workpiece in multi-point forming process. Zhang [10] studied in detail the springback law and springback compensation method of complex curved sheet metal multi-point forming through numerical simulations and experiments.
Ultrasonic vibration research mainly focuses on the drawing of linear materials and heterogeneous materials and the rolling, extrusion, shearing, and punching of plates. The research and application in these aspects have been relatively mature and have been used in actual production, but there are very few studies on ultrasonic vibration-assisted multi-point forming and bending [11–14]. This article mainly focuses on the multi-point forming of aluminum alloy sheets and studies the influence of ultrasonic vibration on the multi-point forming process of sheets.

Aluminum alloy plates are widely used in various fields such as aerospace, automobiles, and electric devices because of their high strength, light weight, and easy processing. 2024-O is a typical hard aluminum alloy in the aluminum-copper-magnesium series, with reasonable composition and high comprehensive performance. Because of its high strength, heat resistance, and corrosion resistance, it is widely used in aviation in aerospace applications, and its elemental composition is shown in Table 1.

2. Forming Principle and Theoretical Basis

Multi-point forming technology is one of the flexible forming methods of sheet metal. Its basic principle is to separate the upper and lower moulds into punches based on traditional mould forming [15]. The punches are regularly arranged, and the upper and lower heights are adjustable. In the basic body group (Figure 2), in traditional integral mould forming, a set of moulds can only form plates of a specific size and shape. In contrast, in multi-point forming, each basic body is independent and controlled by different control systems. A computer can adjust the body to form different sizes and different shapes. The shape of the plate makes the forming die flexible and versatile.

Ultrasound refers to vibration waves whose vibration frequency exceeds 20 kHz. Ultrasound has the characteristics of large oscillation energy, high frequency, and strong penetration. It plays an important role in the field of practice and scientific research. Metal plastic forming means that pressure metal is applied to the metal structure, which makes the metal exhibit plastic deformation to obtain the ideal structure, performance, shape, and size. Research shows that if a certain degree of ultrasonic vibration is applied to the material or the forming mould during the metal-plastic forming process, a phenomenon different from the non-ultrasonic vibration forming will occur, which reduces the forming force of the metal-plastic forming and improves the deformation limit; additionally, the surface quality and accuracy of the product are improved after forming, which reduces the friction between the workpiece and the mould during the forming process [16].

Among the factors that affect the reduction of forming force by ultrasonic vibration-assisted forming, the "volume effect" and "surface effect" occupy a dominant position in theory. The "volume effect" means that the internal stress of the workpiece is affected by vibration, which is interpreted as the principle of stress superposition in a macroscopic sense. The "surface effect" is the effect of frictional vibration on the relative movement between the surface of the workpiece and the mould, and simple tribological models are generally used to explain the distribution of friction under actual conditions. Regarding ultrasonic vibration-assisted metal sheet plastic forming, due to the lack of corresponding theories, qualitative research is much more common than quantitative research [17–19].

2.1. Volume Effects

2.1.1. Non-Local Theoretical High-Frequency Vibration Plastic Material Constitutive Model [20]. Non-local theory refers to the fact that when the outer feature size of the metal material is not negligible compared with the inside of the material, the long-range interaction of the atomic structure must be considered. In ultrasonic vibration-assisted metal plastic forming, the vibration frequency is higher, and the vibration wavelength and internal material size of the microscopic particles are on the same order of magnitude. Therefore, the influence is obvious, and the elongation of the material is obviously reduced. Local theory should be selected to analyze the vibration forming mechanism.

The constitutive equation is

\[ \sigma_{ij} = \int_V E_{klmn}(x', \zeta) \epsilon_{mn}(x') \, dv(x'), \]  

(1)
where $\sigma_{kl}$ is the non-local stress, $E_{klmn}$ is the non-local modulus of elasticity, which is a function of the feature quantity, $\epsilon_{mn}$ is the strain, $|x' - x|$ is the distance between points in space, $\zeta$ represent relevant influencing parameters of the vibration frequency, the integral is the product in the space volume $V$, and the distribution of the strain affects the stress state.

2.1.2. Elastoplastic Constitutive Model [21, 24]

$$\int E_{klmn} \sigma_{kl}(|x' - x|, \omega) \, dv(x') = \frac{\sigma}{\epsilon_0},$$

(2)

where $\sigma$ represents that the yield limit of high-frequency vibration stretching is the yield limit of stretching under normal conditions. On this basis, combined with Jaumann-roll stress rate, the plastic constitutive equation of the material under ultrahigh-frequency vibration is proposed.

$$\sigma_{kl} = -2\nu \frac{\zeta}{\sigma} + \int E_{klmn} \sigma_{kl}(|x' - x|, \omega) \, dv(x'),$$

(3)

where $\sigma_{kl}$ is the deformation rate partial tensor.

If other influences are not considered and only plastic deformation and elastic deformation are considered, the main factors affect the metal deformation, and the constitutive relationship is shown in Figure 3.

In the case of low-frequency vibration, the loading and unloading criteria are $\epsilon \sigma > 0$ (loading); $\epsilon \sigma \leq 0$ (unloading). The elastoplastic constitutive model of the material is shown in Figures 4 and 5 [21, 24].

2.1.3. Elastic-Viscoplastic Constitutive Model [22]. To date, three theoretical models dynamically describe the plastic constitutive relationship, the viscoplastic model, quasi-linear constitutive model, and overstress model. The elastic-viscoplastic model is shown in Figure 6. This model contains viscous, elastic, and plastic components. It consists of three parts and is used to explain the mechanical properties of metals when considering the effect of the metal strain rate.

The stress-strain relationship is as follows:

$$\epsilon = \epsilon_e + \epsilon_v, \epsilon_v = \epsilon_p,$$

$$\sigma = \sigma_e + \sigma_v, \sigma = \sigma_p,$$

$$\sigma_e = E \epsilon_e, \sigma_v = \eta \epsilon_v,$$

(4)

where $\epsilon$ is the overall strain, $\epsilon_e$ is the elastic strain, $\epsilon_v$ is the viscoplastic strain, $\epsilon_p$ is the plastic strain, $\sigma$ is the total stress, $\sigma_e$ is the viscous stress, and $\sigma_p$ is the plastic stress.

He and Wen [23] researched and calculated the yield constitutive relationship.

$$\dot{\epsilon} = \frac{\sigma}{E} + \frac{1}{\eta} \left[ \sigma - (\sigma_p + B \epsilon_p) \right].$$

(5)

B is a linear strengthening parameter under quasi-static conditions. When subjected to low-frequency vibration or ultrasonic vibration, according to the basic assumption of Kirchner et al. [24], the stress and strain of the material will oscillate. The equation of change is the strain and strain rate.

$$\epsilon(t) = \epsilon_0 + A \sin(2\pi ft).$$

(6)

The strain rate is derived from

$$\dot{\epsilon}(t) = \epsilon_0 + 2\pi f A \sin(2\pi ft),$$

(7)

where $A$ is the amplitude, $f$ is the frequency, and $t$ is the time.
In vibration stretching, due to the oscillating strain, the material state alternately changes between elasticity and plasticity. In the elastic phase, the strain rate is not considered. The standard for the transition of the material from the elastic state to the plastic state (elasto-viscoplastic boundary) depends on the instantaneous strain during the deformation process and the yield strength of the material. If the strain satisfies the elasto-viscoplastic boundary condition and the strain rate is greater than zero, then the material elasto-viscosity constitutive model is needed to solve the subsequent stress level; if the subsequent stress meets the elastic boundary condition and the strain is lower than zero, then the material elastic constitutive model is required to solve for subsequent stress levels.

He and Wen [23] studied the stress solution in the elastoplastic state and obtained the dynamic stress solution equation.

\[ \sigma + \frac{(B + E)\sigma}{\eta} = q(t), \]

\[ q(t) = E \left[ \dot{\varepsilon}_0 + 2\pi f A \cos(2\pi ft) + \frac{B\dot{\varepsilon}_0 t + BA \sin(2\pi ft) t}{\eta} + \left( \frac{\sigma_{sp} - B\varepsilon_0}{\eta} \right) \right]. \]

where \( \eta_1 \) is the viscosity coefficient of the elastic part and \( \eta_2 \) is the viscosity coefficient of the plastic part.

According to the model of formula (10), the average stress of one cycle in the vibration plastic process can be obtained as

\[ \sigma(t) = \frac{1}{T} \int_{t_0}^{t_0 + T} \sigma(t) \, dt, \]

where \( T \) is the cycle time and \( t_0 \) is the extreme value of strain.

2.2. Surface Effects. At this stage, the research theory of surface effects is not mature, and the basic friction model, i.e., Coulomb friction and constant friction, is used to describe the actual contact surface. The factors that affect the surface effect mainly include these aspects, local separation caused by vibration, changes in the direction of friction, local thermal effects, and friction at a certain point, which is related to this point and the surrounding area, i.e., non-local effects. Lin et al. [25] introduced an analytical formula for the frictional force of the metal drawing process assisted by vibration.

Non-local friction formula:

\[ \tau(t) = \mu \int_{1} \omega_p(|\tau - \tau|) P(\tau) \, d(\tau), \]

\[ 0 < \rho < 1, \quad 1 - t - \rho \leq t + \rho, \]

\[ \omega_p(t) = \begin{cases} 0 & |t| > \rho, \\ C_0 \exp \left[ \frac{\rho^2}{(t^2 - \rho^2)^2} \right] |t| \leq \rho, \end{cases} \]
where $C_0$ is a constant, $\mu$ is the coefficient of friction, and $\rho$ is the size of the non-local scope which can be obtained by solving

$$
\tau(t) = -[(\sigma_s - E' \epsilon_p) + 2E' (\dot{\epsilon} t)]\tan \alpha - \left[ K + Gt + A_1 \sin \left( \frac{1 + B}{\epsilon_0} t \right) + A_0 \sin(2\pi ft) + A_2 \cos \left( \frac{1 + B}{\epsilon_0} t \right) \right] \tan \alpha.
$$

Average value of friction:

$$
\bar{\tau}(t) = \frac{1}{T} \int_{t_0}^{t_0 + T} \tau(t) dt,
$$

where $\epsilon_0$ is the non-local friction coefficient, $\sigma_s$ is the initial yield point, $E'$ represent the linear enhancement parameters under quasi-static conditions, $\epsilon_p$ is the initial yield strain point, and $\dot{\epsilon}$ is the strain rate.

Based on previous theoretical research, we clarify the theoretical basis of the effect of ultrasonic vibration on the formation of metal material properties and the plastic constitutive model of metal materials. Therefore, the introduction of ultrasonic vibration into the plastic processing of metals shows that ultrasonic vibration can reduce the external force required for material deformation and improve the surface quality of products, based on two theoretical foundations: volume effect and surface effect.

### 3. Finite Element Model

In the plastic deformation process, different materials can exhibit vast differences. This article mainly focuses on the forming of a pipe surface. The effect of ultrasonic vibration on the springback, thickness, stress, and strain at the forming end is experimentally studied. The results provide a basis for reference.

#### 3.1. Establishment Model and Material Parameters

This article mainly focuses on single curvature arc surface forming as the main research object. The formed radius is 400 mm, the sheet size is 210 mm $\times$ 210 mm, the size of the elastic pad is 210 mm $\times$ 210 mm, and the thickness is 5 mm. The number of basic body groups is 11 $\times$ 11, the diameter of each punch is 16 mm, and the width between each basic body is 20 mm. Since the effect of the parameters of the elastic pad on the results is negligible, the elastic pad is simplified to a linear elastic model, and the parameters are as follows: the density is 1126 kg/m$^3$, Poisson’s ratio is 0.49, and the modulus of elasticity is 100 GPa. This article mainly studies the forming situation of the sheet, so the basic body group of the model can be simplified to a rigid body that cannot be deformed. The assembly model is shown in Figure 2.

#### 3.2. Meshing and Element Types

In the same model, the mesh division of the research object will change accordingly, and the quality of the mesh directly affects the accuracy of the analysis results. In principle, we can use sparse grids for the parts that are of minimal concern or have little effect on the results, which can speed up the calculation. We divide the parts that we care about into denser grids, and different research objects use different types of grids. Thin plates are the main research object in this paper, the primary concerns of which are the thickness of the thin plate and the changes in stress and strain. It is easy to self-lock with the quadratic integral element, and the thickness of the plate is much smaller than the width, so the S4R four-node curved shell element is used. The thickness is 3 mm. The function of the elastic pad is mainly to prevent stress concentration, and the force of the elastic pad is not the main concern, so a sparse grid can be used to increase the calculation speed; the grid size is 5 mm, and the grid type is a C3D8R eight-node linear hexahedral element. Similarly, for the convenience of calculation, the basic body group is coupled into a rigid body in one column, and the mesh is divided as little as possible. Therefore, the S3R three-node triangular shell element is used, and the mesh width is 1 mm.

#### 3.3. Contact and Friction

To simulate the real interaction in Abaqus, there are two algorithms to select contact types: the contact pair algorithm and contact algorithm. For the contact between the basic body group, elastic pad, and thin plate, we use general contact, and the contact properties are set for tangential behavior and normal behavior. Friction is a very complex physical model that is affected by various factors. This article adopts Coulomb's law of friction, and its formula is

$$
\tau_{\text{crit}} = \mu \sigma,
$$

where $\sigma$ is the positive pressure and $\mu$ is the coefficient of friction.

Because it is very difficult to simulate the ideal friction behavior, to avoid penetration between the contact surfaces, Abaqus provides a friction theory that allows “elastic sliding,” called a penalty function. In this paper, a penalty function is used to constrain the finite element model. The coefficient of friction of 0.1 is set between the thin plate and
the elastic pad, the elastic pad and the basic body group, and the elastic pad is urethane pad [26].

3.4. Setting of Boundary Conditions and Loads. The setting of boundary conditions and loads is directly related to the correctness of the results in the finite element simulation. The loading of boundary conditions is mainly divided into two situations, by limiting the displacement or the load. The load is limited by the displacement, and the bending height of the basic body group is controlled to bend and form the thin plate. At the beginning of the moulding process, only the basic body groups must be evenly arranged on the upper and lower surfaces of the elastic plate. Then, the respective basic bodies are individually pressed and displaced.

4. Numerical Analysis of the Forming Results

4.1. Analysis and Comparison between Vibration and Non-Vibration. Finite element simulations of the 2 mm-thick sheet at a frequency of 20 kHz and amplitude of 9 μm and the 2 mm-thick sheet with no vibration were performed. The ultrasonic loading time was 1 s, and analysis and comparison were performed.

4.1.1. Stress Analysis. For stress analysis of the thin plate before unloading, Figure 8 presents a schematic diagram of the vibration-free von Mises stress distribution of a single curvature arc with a radius of 400 mm. Figure 9 presents a schematic diagram of the stress distribution at 20 kHz and 9 μm amplitudes.

Before unloading, the maximum stress of the thin plate without ultrasonic vibration was 72.35 MPa, which appeared in the middle position, and the minimum stress was 12.35 MPa, which appeared in the welt position. The maximum stress of 20 kHz and 9 μm amplitude ultrasonic vibration is 69.06 MPa, and the minimum stress is 11.79 MPa. The maximum stress is reduced by 4.5%, and the minimum stress is reduced by 4.5%.

The force of the auxiliary forming process by ultrasonic vibration is significantly better than the former approach. The stress distribution is more uniform, the stress concentration area is reduced, and the maximum and minimum stresses are also reduced accordingly.

4.1.2. Strain Analysis. Figure 10 shows the forming results of applying ultrasonic vibration with a frequency of 20 kHz and an amplitude of 9 μm, and Figure 11 shows the results of vibration-free forming.

Under identical conditions, ultrasonic vibration with a frequency of 20 kHz and an amplitude of 9 μm is applied. Comparing Figure 12, we observe that the maximum plastic strain of the thin plate with ultrasonic vibration is 0.00098, and the model plastically deforms with ultrasonic vibration. The area has significantly increased.

4.1.3. Springback Analysis. Under identical frequency and amplitude, springback analysis of a 2 mm-thick sheet is performed. The sub-displacement cloud diagram of the displacement along the Z-axis direction under vibration and the sub-displacement cloud diagram along the Z-axis direction under the condition of no vibration are presented for comparison, as shown in Figures 12 and 13.
According to the data derived from the results, a dotted-line diagram of the displacement along the Z axis in the two states is drawn, as shown in Figure 14. From Figure 15, the maximum springback displacement occurs at the edge of the thin plate when there is no vibration, and the springback amount is 8.756 mm. When there is vibration, the maximum springback is 7.037 mm, and the springback is reduced by 19.6% compared to the non-vibration model.

4.2. Comparison of the Situation When the Vibration Time Is Different. The vibration loading time was changed to 0.5 s and 2 s, respectively. Compared with the previous loading time of 1 s, the rest of the parameters were unchanged, and the effect of time on the stress, strain, and springback in the forming situation was studied.

4.2.1. Stress Comparison. Figure 15 shows the stress change cloud diagram of a 2 mm-thick sheet with a 0.5 s ultrasonic loading time at 20 kHz frequency and an amplitude of 9 \( \mu \)m. Figure 16 shows the stress change cloud diagram of a 2 mm-thick sheet with a 2 s ultrasonic loading time at 20 kHz frequency and an amplitude of 9 \( \mu \)m.

Comparing the stress diagrams of 0.5 s, 1 s, and 2 s, the maximum stress is 72.3 MPa, 66.3 MPa, and 60.9 MPa, respectively. When the ultrasonic vibration time increases, the stress also decreases accordingly. In addition, the force is best when it is approximately 1 s.

4.2.2. Strain Comparison. The strain diagram when the loading ultrasonic vibration time is 0.5 s and other parameters remain unchanged is shown in Figure 17. The strain diagram when the loading ultrasonic vibration time is 2 s and other parameters remain unchanged is shown in Figure 18.

By comparing three strain diagrams with different vibration times, it is found that there is no significant change in size of the strain area. Therefore, time has no obvious relationship with the size of the strain area and the time of ultrasonic vibration loading.

4.2.3. Springback Comparison. If the ultrasonic vibration frequency and amplitude remain unchanged, springback analysis is performed after changing the loading time, and the analysis results are shown in Figures 19 and 20.

Comparing the loading times of 0.5 s, 1 s, and 2 s and the springback without vibration, we find that the maximum springback occurs at the edge of the plate, and the largest occurs without vibration, followed by the springback at 0.5 s, 1 s, and 2 s. When the amount is larger than 1 s, applying ultrasonic vibration for approximately 1 s has a better effect on the result.

Figure 21 shows that the overall effect of vibration of approximately 1 s is the best. It significantly affects the edge of the plate at 0.5 s, but the intermediate effect is not good. At 2 s, the springback reduction effect of the middle part of the plate is obvious.
5. Ultrasonic Vibration Controlled Multi-Point Forming Test of Sheet

To verify the effect of ultrasonic vibration control on reducing the springback of sheet metal multi-point forming, ultrasonic vibration control multi-point forming tests of specimens with different loading times, sheet thicknesses, and shapes were performed.

The forming part of the multi-point forming equipment is shown in Figure 22. The basic body group adopts an 11 × 11 arrangement. Each of the upper and lower basic body group has 121 basic bodies and creates a forming area of 200 mm × 200 mm. The upper and lower basic body punch groups are included in the upper and lower mounting bases. The curved surface of the basic body punch group uses CAD...
technology to describe the target surface shape of the required forming sheet. Then, computer-aided geometric design is used to calculate the contact point between the basic body and the sheet. The height parameters that must be adjusted for each basic body are calculated, so that the upper and lower basic body group strokes require the forming of a surface. The upper and lower basic body groups are adjusted up and down by the three-coordinate manipulator, so that the plate can obtain the desired target shape.

A multi-point mould is used for the forming test, and the shape of the mould surface is adjusted according to the shape obtained by fitting. The size of the forming surface of the test equipment is larger than the size of the formed part, and the non-formed area can be leveled without affecting the forming.

The plate material used in the experiment is pure aluminum plate, and the thickness of the plate is 1 mm, 1.5 mm, 2 mm, and 3 mm. The objective shapes are cylindrical and saddle. Saddle-shaped target curvature $K_x = K_y = 0.5 \text{ m}^{-1}$; cylinder target curvature is $0.5 \text{ m}^{-1}$. The ultrasound frequency is 20 kHz, 30 kHz, and 40 kHz.

5.1. Ultrasonic Excitation Method Reduces the Effect of Springback. Figure 23 shows the test result for a specimen with a plate thickness of 1.5 mm and a cylindrical target shape formed at different high frequencies.

In this experiment, four basic body group forming surfaces that gradually tend to the final target shape are used. If there is no springback, the shape of the sheet should be exactly identical to the shape of the forming surface after each forming. Since springback is inevitable during the sheet metal forming process, the actual deformation must deviate from the ideal non-springback deformation, and the deviation is the springback.

The experimental results in Figure 23 show that for a metal sheet of the same thickness, different applied ultrasonic frequencies have different springback effects on the sheet. With a suitable frequency, the elastic recovery of the specimen is stable and reaches the target size.

5.2. Influence of Plate Thickness on Springback in Multi-Point Forming by Ultrasonic Vibration. The thickness of the plate greatly affects the springback, and the ultrasonic excitation method can stabilize the plates of different thicknesses at the target size.

Figure 24 shows the experimental results of a specimen with a saddle-shaped target shape and four thicknesses after the ultrasonic excitation method.

In the multi-point forming process controlled by ultrasonic excitation, with the increase of high-frequency excitation frequency, the springback of different plate
thicknesses gradually decreases. The specimens eventually converge to the target shape.

In the process of ultrasonically excited multi-point forming, the peak point of the residual stress in the specimen increases and the peak value decreases. Therefore, the increase in excitation frequency of ultrasonic-excited multi-point forming can more effectively reduce springback and residual stress. However, for different plate thicknesses, it is very important to select a reasonable excitation frequency and time. To accurately give the optimal number of repeated forms, it must be determined after comprehensive analysis of various deformations such as different materials, sizes, and target deformations.

6. Conclusions

Through numerical analysis and experiments to compare two schemes of multi-point forming of thin plates with and without ultrasonic vibration, the following conclusions can be drawn:

(1) The stress of the thin plate is effectively reduced after ultrasonic vibration is applied. The decrease in internal stress significantly affects the decrease in springback.

(2) In terms of strain, after applying the ultrasonic vibration, the plastic strain area is significantly extended, i.e., the deformation of the thin plate is more uniform.

(3) Compared to the model with no vibration, the model with ultrasonic vibration effectively reduces the springback. The effect is more significant due to the shorter time of action.

(4) Among different vibration loading times, 1 s loading shows the best performance. The stress is small, the strain area has no obvious change, and the improvement effect on springback is the most pronounced.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

The file titled “Supplemental Files” contains all the test data. (Supplementary Materials)

References


