Deformation characteristics and forming force limits of multi-point forming with individually controlled force–displacement

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Abstract
To solve the problem of springback in traditional multi-point forming (MPF), a new multi-point forming process, namely, multi-point forming with individually controlled force–displacement (MPF-ICFD), is proposed. In this manuscript, traditional MPF and MPF-ICFD are compared. Taking the cylindrical surface as the research object, the change in the springback of a plate is analysed by experiments, and the distribution of the strain and wall thickness of the plate is analysed by numerical simulation. Theoretical analysis is used to calculate the forming window for the MPF-ICFD process, and the results from theoretical analysis are verified by experiments and numerical simulation. The results show that the springback of 1060 aluminium alloy and Q295 for MPF-ICFD can be decreased by 73.8% and 45.5%, respectively, compared with traditional MPF. In traditional MPF, the strain uniformity of the plate is poor, and the maximum thinning rate is 4.5%. For MPF-ICFD, the strain is relatively uniform, and the maximum thinning rate is 0.25%. For an aluminium alloy sheet with a wall thickness of 1.5–3 mm, the upper and lower limits of the forming force for a single head are observed to change linearly from 6.3 to 12.6 kN and from 0.5 to 1 kN, respectively.

Keywords Multi-point forming · Normal force · Springback · Forming window

1 Introduction

Traditional sheet metal stamping technology is widely used in the aerospace, automobile and other fields. However, the initial investment of stamping equipment is large, and the design and production cycle of the stamping die is long, so the technology has significant economic benefits only for mass production [1, 2]. In recent years, with the development of market globalization and product customization, flexible manufacturing technology has received increasing attention [3, 4].

Multi point forming (MPF) is a typical flexible manufacturing technology that is very suitable for manufacturing small batch sheet metal parts [5]. Springback is an inevitable phenomenon in MPF or other stamping processes, and it has a negative effect on the geometric size of the workpiece [6]. Springback compensation is one of the main methods used to solve the springback problem. There are two basic ideas: First, the shape of the plate after springback is predicted through theoretical analysis, that is, the relevant theory of elastoplastic mechanics is used to establish a mechanical model matching the forming process, calculate the shape of the plate after springback, obtain the forming error for the plate and then obtain the corresponding compensation. Second, the springback of sheet metal through numerical simulation is predicted, that is, numerical simulation software is used to establish a numerical model matching the forming process through simplification and analysis, simulate the shape of sheet metal after springback and obtain the corresponding compensation. According to the compensation obtained by theoretical analysis or numerical simulation, the die surface is designed to ensure that the shape of the workpiece after springback is consistent with the target shape [7, 8].

Li et al. [9] proposed a bending moment calculation model for variable curvature sheet metal bending, which can be used to predict the springback of sheet metal. The stress and strain in the model consider the geometrical characteristics of the workpiece contour, which can accurately reflect the internal
force for the plate. Zhang et al. [10] proposed a springback compensation algorithm for sheet metal forming with a hyperbolic surface. This algorithm is based on the ideal elastic–plastic biaxial bending model. The springback compensation surface is described by the combination of difference processing and a Bézier surface, which can be used to effectively control the springback error for the MPF of the hyperbolic surface. In fact, springback compensation models have been rapidly developed in recent decades. However, stamping involves a complex plastic deformation process including geometric nonlinearity, material nonlinearity and contact nonlinearity. The theoretical model has difficulty in fully considering the above factors, so its accuracy is limited [11, 12].

With the rapid development of computer technology, finite element simulation is considered to be an effective method to predict springback in sheet metal stamping [13, 14]. Panthi et al. [15] proposed a finite element model that can be used to consider the influence of geometric parameters, material mechanical properties and contact conditions to predict the springback of sheet metal bending. The simulation results were found to be in good agreement with the experiments. Esat et al. [16] simulated the springback for bending aluminium alloy with different grades and thicknesses and analysed the equivalent plastic strain and the equivalent Mises stress. The numerical simulation can be used to accurately provide mould compensation and significantly reduce the test time and cost [17]. However, the springback compensation method has some limitations. For workpieces with a large curvature, some forming defects (e.g. wrinkling and fracture) can be formed by overcompensating for springback [18].

Many researchers have found that changing the process method to optimize the mechanical conditions for sheet metal deformation is an effective method to reduce springback [19]. Zhang et al. [20] proposed the idea of multi-point sandwich forming. In this process, the die consists of a reconfigurable lower die and a rubber pad upper die. A backing plate is placed onto the upper side of the lower die to form a continuous surface. In the forming process, the rubber pad remains in contact with the blank and produces a normal force on the sheet. The normal force can reduce the springback moment for sheet metal deformation, thus reducing the springback amount. Liu et al. [21] proposed a multi-point hydroforming method by replacing the traditional hydroforming solid mould with a multi-point mould. Under a real-time controlled hydraulic pressure, the uniformity of the normal force and sheet deformation can be significantly improved, which is beneficial for further reducing the springback. However, the above process can only be used to apply a normal force on one side of the sheet and cannot fundamentally change the stress conditions for the sheet, so the springback inhibition effects of current methods remain limited.

The authors of [22] proposed a multi-point forming process with individually controlled force–displacement (MPF-ICFD), which can obviously restrain the springback of sheet metal. In this process, both the upper and lower sides of the sheet are subject to a fully controllable normal force. When forming, the neutral layer of the sheet moves inward, the springback moment is significantly reduced and the amount of springback of the sheet is significantly reduced. In previous studies, the feasibility of the MPF-ICFD process has been verified [23], but more in-depth studies, e.g. springback characteristics, wall thickness distribution and forming force limits, which are important for the application of a new technology, still require further discussion. In this work, the deformation characteristics for sheet metal in MPF-ICFD are studied. The forming limit pressure is deduced by theoretical analysis. The equivalent plastic strain and thickness distribution are analysed by numerical simulation. The springback characteristics and forming force limits for sheet metal are studied using experiments.

## 2 Technical principle

### 2.1 The principle of MPF-ICFD

The principle of MPF-ICFD is shown in Fig. 1. Each lower punch is controlled by a hydraulic cylinder that can move independently. The forming process is divided into three stages. In the initial stage (Fig. 1a), the heights of the upper punches are adjusted so that the surface formed by the connection of the punch vertices is symmetrical to the target surface. The hydraulic cylinders force the lower punches to move upwards. The upper punch and die frame are connected by springs. Under the action of an external force, the upper punch can move in the die frame hole along the plumb direction. When no external force is applied, the upper punch is located at the upper limit position under the action of the spring force. When the upper punches are pushed to the upper limit point, the sheet is clamped between the upper and lower punches. The force between the upper and lower punches is balanced by the die frame. During the forming process, the loading curve for the hydraulic cylinder pressure is shown in Fig. 1d. In the forming stage (Fig. 1b), the slider of the press moves downwards, first pressing the highest punch $S_1$ and $S_3$, and the sheet in the corresponding area is deformed. As the slider continues to move, $S_2$, $S_4$ and $S_1$ move down sequentially. The movement curves for the punches are shown in Fig. 1d. At the final stage (Fig. 1c), the hydraulic cylinders force the lower punch to move downwards to the lower limit position, and the slider of the press moves upwards. The upper punch moves to the upper limit position under the action of the spring force to remove the workpiece and complete the whole forming process.

### 2.2 Advantages of MPF-ICFD

In the process of MPF-ICFD, a new contact state between the sheet metal and die is produced, which allows for unique
Advantages during the process. First, the contact condition between the sheet metal and punches is improved. By applying a hemispherical hinge structure at the head of the punches, the point contact in the traditional MPF process is changed to a face contact. The whole contact surface can rotate with the deformation of the sheet, and the normal force is constantly applied onto the sheet, which can improve the stress uniformity. Second, the plastic deformation is more uniform. The deformation sequence for the sheet metal changes from local constraint global deformation in the traditional MPF process to global constraint local deformation, which can improve the uniformity of the plastic deformation. Third, the material utilization rate is high. Each punch plays the role of a blank holder during forming, which is equivalent to a full-area flexible blank holder. No special blank holder is required, which improves the material utilization.

3 Materials and methods

3.1 Material

1060 aluminium alloy and low carbon steel (Q295) were selected as the experimental materials. The mechanical properties of the plate were determined by uniaxial tensile testing. The specific test methods are as follows: First, the uniaxial tensile specimen is designed according to GBT228.1–2010. The specimen is cut by wire cutting along the direction oriented 90° to the rolling direction. The specimen size is shown in Fig. 2. Second, 100–1000 # metallographic sand paper was used to polish the cutoff sample until the surface was bright, flat and free of gaps to eliminate the impact of wire cutting on the mechanical properties of the sample. Third, the true width, thickness and gauge length of the sample were measured with a Vernier caliper to obtain the original size data for the

![Fig. 1 Forming principle of MPF-ICFD](image1)

![Fig. 2 Tensile specimen size and true stress–strain curve for 1060 aluminium alloy and Q295](image2)
sample. Fourth, the specimen was installed into an Instron 5569R electronic universal testing machine, and the test was carried out at a strain rate of 0.001/s at room temperature using an extensometer with a gauge distance of 50 mm. The measured true stress–strain curve for the plate is shown in Fig. 2. Before forming, the sheets were annealed to eliminate the influence of anisotropy. In subsequent experiments and analysis, the sheets were regarded as isotropic [24].

3.2 Method

A cylindrical surface part is selected as the target, as shown in Fig. 3. In the first group, the contrast experiments for traditional MPF and MPF-ICFD were carried out to study the difference in the characteristics of springback and deformation. In the second group, the forming force limits were studied by changing the forming force, which is defined as the force exerted by a single hydraulic cylinder. The specific experimental scheme is shown in Table 1. In the first group, the same clamping force was applied for traditional MPF and MPF-ICFD. In the second group, the forming force was selected at steps of every 50 N near the critical value according to the theoretical analysis results. The upper limit was analysed by numerical simulation, and the lower limit was tested by experiment. The blank size was 200 mm × 200 mm.

3.3 Experimental setup

The schematic diagram and experimental setup are shown in Fig. 4. The upper die consisted of 100 adjusting screws (the adjusting stroke is 0–50 mm) and punches. The lower die consisted of 100 hydraulic cylinders (the maximum forming force of a single hydraulic cylinder was 2850 N) and punches. The punch head consists of a hemispherical hinge structure that can swing with the deformation of the sheet, with a deflection angle of 0–45°. The forming area of the die was 200 mm × 200 mm.

3.4 Finite element model

ABAQUS/explicit was used to establish a finite element model of MPF-ICFD. Because of the bending deformation in the forming process, the thickness dimension of the sheet is much smaller than the dimensions in the other two directions, so the shell element was used to build the sheet model. The sheet was set as an elastic–plastic and isotropic material. The element type was S4R, and the mesh size was 5 mm × 5 mm. The head was set as an analytical rigid body, and the cell type was S4R [25]. The contact type between the head and the sheet was set to face-to-face contact. The friction coefficient between the head and aluminium alloy was set to 0.17, as determined by using a HT-1000 friction coefficient tester [26]. Figure 5 shows the numerical model for MPF-ICFD, and the traditional MPF for the finite element model is established according to the same method.

4 Analysis of the forming window

In the process of MPF-ICFD, the sheet metal is always clamped by the punch heads and can slide between the upper and lower heads, so there are upper and lower limits for the forming force applied to the sheet metal. The lower limit should meet the requirement for the head to clamp the sheet metal. When the forming force is lower than the lower limit, the head cannot clamp the sheet metal in the forming process, which will lead to defects related to insufficient forming. The upper limit shall meet the relative movement demand between the sheet and head. When the forming force exceeds the upper limit, the sheet cannot slide between the heads, resulting in thinning and cracking defects. Next, the

| Group | Technology      | Material   | Forming force (N) | Sheet thickness (mm) | Forming speed (mm/min) |
|-------|-----------------|------------|-------------------|----------------------|------------------------|
| 1     | MPF/MPF-ICFD    | 1060/Q295  | 2500              | 2                    | 5                      |
| 2     | MPF-ICFD        | 1060       | -                 | 1.5/2/2.5/3          | 5                      |
mechanical analysis for MPF-ICFD was carried out, and the extreme value for the forming force is discussed. Taking a cylindrical surface as the research subject, the following assumptions can be made [27]: (1) The assumption of stamping bending theory is adopted. (2) The properties of the sheet yield are consistent with the bilinear yield model. (3) The force exerted by the head on the sheet is evenly distributed on the sheet surface. (4) The middle layer of the sheet coincides with the neutral layer.

4.1 Lower limit for the forming force

In the process of MPF-ICFD, the head is moved row by row, and the minimum forming force appears at this moment. When the deformation reaches the $i^{th}$ row of heads (row $i^{th}$ represents any one of the punches), the lower head of the $i^{th}$ row cannot support the sheet, so the upper head at this position loses its constraint on the sheet. Figure 6 shows the contact state and stress analysis for the head and sheet when the forming force is in the lower critical state. The head is connected to the punch by a magnetic force, which can rotate flexibly and continuously exert a normal forming force on the sheet.

In the critical state, the deformation of the sheet metal needs to meet two conditions at the same time: The first condition is that the sheet at the $i^{th}$ row of $F_f$ experiences plastic deformation, and the second condition is that the deflection at the $i^{th}$ row of $F_f$ is zero.

As shown in Fig. 6, $F_d$ is the forming force of the upper head, $F_f$ is the forming force of the lower head and $\Delta l$ is the distance between the two heads.
It can be observed from the first condition that in the width range of $\Delta l$, the bending moment $M_{F_f}$ at the action point of $F_f$ is

$$M_{F_f} = F_c \Delta l$$

where $F_c$ is the resultant force for the upper and lower heads and $M_{F_f}$ is the bending moment at the action point of $F_f$.

From the calculation formula for the bending moment, the following formula can be obtained:

$$F_c = \frac{W \sigma_s}{\Delta l} \left( \frac{3}{2} - \frac{2\sigma_s^2 \rho_0^2}{E^2 t^2} \right)$$

where $\sigma_s$, $E$ and $t$ are the yield strength, elastic modulus and thickness of the sheet, respectively, $W$ is the bending section coefficient and $\rho_0$ is the curvature radius at the neutral layer.

In the $i^{th}$ row, the deflection upon the action of $F_f$ is generated by $F_c$ and $F_f$, and the deflection values for the two are determined as follows:

$$f_{F_c} = \frac{5F_c \Delta l^3}{6EI}$$

$$f_{F_f} = \frac{-F_f \Delta l^3}{3EI}$$

where $f_{F_c}$ is the deflection of $F_c$ in the $i^{th}$ row and $f_{F_f}$ is the deflection of $F_f$ in the $i^{th}$ row.

From the second condition, we can obtain the following relations:

$$f_{F_c} + f_{F_f} = 0$$

(5)

By combining Eqs. (2)–(5), we can obtain the following:

$$F_f = \frac{5F_c}{2} - \frac{F_c}{2\Delta l} \left( \frac{3}{2} - \frac{2\sigma_s^2 \rho_0^2}{E^2 t^2} \right) = \frac{5\beta r^2 \sigma_s}{12\Delta l} \left( \frac{3}{2} - \frac{2\sigma_s^2 \rho_0^2}{E^2 t^2} \right)$$

(6)

In Formula (6), $F_f$ is the minimum value of the resultant force for each row of heads along the sheet width direction, so the minimum value for the forming force of each head is given by

$$F_{min} = \frac{F_f}{k} = \frac{5\beta r^2 \sigma_s}{12k \Delta l} \left( \frac{3}{2} - \frac{2\sigma_s^2 \rho_0^2}{E^2 t^2} \right)$$

(7)

where $k$ in the formula is the total number of heads along the width of the sheet.

In the central area of the sheet, there is a limit case, as shown in Fig. 7. When only the last row of heads in the centre is left as support and all the surrounding sheet has been formed, the final area is formed through bulging due to the large normal forming force of the heads around the centre. The forming force of the lower head at this time is $F_{f'}$. Because the acting area and bulging area for the force are very small, the last row of heads can be approximately considered as a uniform distribution for the forming force. At this time, the upper head does not provide a forming force.

Figure 8 shows the stress in the bulging area. Since the forming force of the lower head is $F_{f'}$, the force balance equation in the $y$ direction is expressed as follows:

$$f_{F_{c'}} + f_{F_{f'}} = 0$$

(5)
Since there is no reaction force on the upper head, i.e. the third main stress (normal compressive stress) is zero, the following relationship can be obtained from the geometric relationship and yield conditions shown in Fig. 8:

\[ F' = \sigma_0 bt \cdot \sin \theta \cdot 2 = 0 \]  

(8)

\[ F' = \frac{bt \Delta l}{\rho_0} \sigma_s \]  

(9)

\[ F'_f, \text{ given by Eq. (9), is also the minimum value of the resultant force for each row of heads along the sheet width direction, so the minimum value of the forming force for each head is given by} \]

\[ F'_\min = \frac{bt \Delta l}{k \rho_0} \sigma_s \]  

(10)

According to the above analysis, the lower limit for the forming force should be selected from the maximum value determined by Formulas (7) and (10).

### 4.2 Upper limit for the forming force

In the MPF-ICFD, the sheet slides between the upper and lower heads. The tangential friction between the heads and sheet can generate an additional tangential tensile stress \( \sigma_{\Delta T} \) on the section of the sheet. When the forming force is too large, the sheet is clamped by the head and no longer slides, resulting in thinning or cracking of the unconstrained part between the two rows of heads. Figure 9 shows the deformation state of the sheet upon thinning or cracking.

To prevent thinning or cracking, the additional tangential tensile stress should meet the mechanical condition shown in Formula (11):

\[ \sigma_{\Delta T} < \sigma_s \]  

(11)

The maximum value of the forming force for which the sheet can move freely in the middle of the punch heads is given by

\[ F_{\max} = \frac{2bt}{n' \mu} \sigma_s \]  

(12)

where \( n' \) is the number of punch columns perpendicular to the tensile direction.

\[ F' = \frac{bt \Delta l}{\rho_0} \sigma_s \]

\[ F'_f, \text{ given by Eq. (9), is also the minimum value of the resultant force for each row of heads along the sheet width direction, so the minimum value of the forming force for each head is given by} \]

\[ F'_\min = \frac{bt \Delta l}{k \rho_0} \sigma_s \]  

(10)

According to the above analysis, the lower limit for the forming force should be selected from the maximum value determined by Formulas (7) and (10).

### 5 Results and discussion

Figure 11 shows the experimental results obtained for Group 1. Next, the springback, strain and wall thickness of the sheet metal for different processes are discussed, and the forming window of the sheet metal in MPF-ICFD is analysed.

#### 5.1 Springback

As shown in Fig. 11, for the 1060 aluminium alloy, in traditional MPF, the workpiece shows a large deviation from the target surface, and the closer one is to the edge, the greater the deviation. For MPF-ICFD, the workpiece is very close to the target surface. The same deformation law is found in the experiment for the Q295 steel sheet.
A 3D scanner was used to measure the contour of the workpiece, and the centre line was extracted and compared with the centre line of the target surface, as shown in Fig. 12. It can be observed more clearly from Fig. 12 that for the 1060 aluminium alloy, the springback for traditional MPF is 34.6% and that for MPF-ICFD is 7.5%, which represents a reduction in springback of 78.3%. For the Q295 steel sheet, the springback for traditional MPF is 31.2% and that for MPF-ICFD is 17%, which represents a reduction in springback of 45.5%.

The springback amount $\eta$ is used to quantitatively analyse the degree of springback of the workpiece, and the specific calculation method is shown in Formula (13):

$$\eta = \frac{\bar{k}_{bs} - \bar{k}_{as}}{\bar{k}_{bs}} \times 100\%$$

In this formula, $\bar{k}_{bs}$ is the average curvature of the target surface, and $\bar{k}_{as}$ is the average curvature of the workpiece. For the workpiece, the contour centreline is fitted as a circle, and the curvature of the fitted circle is taken as the average curvature of the workpiece. For the 1060 aluminium alloy, the springback for traditional MPF is 34.6% and that for MPF-ICFD is 7.5%, which represents a reduction in springback of 78.3%. For the Q295 steel sheet, the springback for traditional MPF is 31.2% and that for MPF-ICFD is 17%, which represents a reduction in springback of 45.5%.

Figure 13 shows the numerical simulation result for the 1060 aluminium alloy springback corresponding to the first group of experiments. The numerical simulation result shows the same change rule as found from the experimental result. That is, for traditional MPF, the springback of the workpiece is large, and for MPF-ICFD, the springback of the workpiece is significantly reduced, which shows that the numerical simulation results have high accuracy.

### 5.2 Distribution of the strain and wall thickness

Figure 14 shows the strain and thickness distribution for 1060 aluminium alloy for traditional MPF. The plastic deformation is mainly concentrated in the central area, and no plastic deformation occurs in the edge area. This is a typical deformation feature of traditional MPF, that is, the deformation mainly occurs in the central area, and it is easy to produce indentation defects due to the large amount of deformation, and the edge area contains straight edge effect defects due to the lack of plastic deformation. The thickness of the central area is obviously reduced, while the thickness of the edge area is unchanged, and the maximum thinning rate is 4.5%.
Figure 15 shows the strain and thickness distribution for the 1060 aluminium alloy in MPF-ICFD. Compared with traditional MPF, the uniformity of the strain and thickness distribution of the sheet metal are significantly improved. The maximum strain for the sheet appears in the edge area, and the plastic deformation is more uniform as a whole. The thickness of the edge area is slightly smaller, the thickness of the centre area is larger and the maximum thinning rate is 0.25%.

5.3 Forming window

Figure 16 shows the experimental results obtained for Group 2 and shows the forming range for the 1060 aluminium alloy with four thicknesses. Because the maximum forming force for a single hydraulic cylinder in the die is 2850 N, which does not reach the upper limit of the forming force for the four different sheet thicknesses in Group 2, the upper limit value shown in Fig. 16 is obtained...
by theoretical calculation and numerical simulations, and the lower limit value is obtained by theoretical calculations and experiments. The damage initialization criterion for metal cracking is ductile damage. The specific parameters are shown in Table 2, and the corresponding energy consumption value is set to 0.02 [28]. At the same time, a 1060 aluminium alloy with a thickness of 0.5 mm is selected in the experiment to determine the deformation characteristics for the specimen with an over-clamped area. It can be observed from Fig. 16 that the theoretical calculation, numerical simulation and experiment show the same change law. That is, the upper and lower limits for the forming force increase with increasing sheet thickness, and the upper limit for the forming force is greatly affected by the sheet thickness, while the lower limit is less affected by the sheet thickness.

To reveal the deformation characteristics for different forming sections, the contact state between the sheet and head in different forming sections is shown in Fig. 17. As the forming force exceeds the upper limit value, the friction between the head and the sheet increases, and the head cannot swing with the sheet deformation during the forming process. This results in a stepped deformation for the sheet in the suspended area between the two rows of heads, resulting in thinning and cracking defects. When the forming force is lower than the lower limit value, the head cannot clamp the sheet; therefore, there is a gap between the sheet in the central area and upper head, and the deformation in this area is small or no deformation occurs, leading to defects due to the sheet metal being under formed. Only when a reasonable forming force is applied can the head always hold the sheet and swing with the sheet deformation, leading to sequential deformation of the sheet from the edge area to the centre area, following which the qualified workpiece can be obtained. For an aluminium alloy sheet with a wall thickness of 1.5–3 mm, the upper limit value of the forming force of a single head changes linearly from 6.3 to 12.6 kN, and the lower limit value of the forming force for a single head changes linearly from 0.5 to 1 kN.

Table 2  Ductile damage parameter

| Number | Fracture strain | Stress triaxiality | Strain rate |
|--------|-----------------|--------------------|-------------|
| 1      | 5.7268          | 0.000              | 0.001/s     |
| 2      | 4.0303          | 0.067              | 0.001/s     |
| 3      | 2.8377          | 0.133              | 0.001/s     |
Conclusions

In this paper, the deformation characteristics and forming window for sheet metal in MPF-ICFD are studied through numerical simulation, mechanical analyses and experiments. The main conclusions are summarized as follows:

1. Compared with the traditional MPF, in MPF-ICFD, the springback of the sheet metal is significantly reduced, and the uniformity of the strain and thickness distribution is significantly improved. For the 1060 aluminium alloy and Q295 steel sheet with a thickness of 2 mm, the springback is decreased by 78.3% and 45.5%, respectively. For 1060 aluminium alloy with a thickness of 2 mm, the maximum thinning rate is decreased from 4.5 to 0.25%.

2. In MPF-ICFD, the lower limit of the forming force should meet the requirements of the head to clamp the sheet metal. When the forming force is lower than the lower limit, the head cannot be used to clamp the sheet metal during the forming process, which will result in defects due to the sheet metal being under formed. The upper limit of the forming force must meet the demand of the relative movement between the sheet and the head. When the forming force exceeds the upper limit, the sheet cannot slide between the heads, resulting in thinning and cracking defects.

3. The upper and lower limits of the forming force in MPF-ICFD are derived by theoretical analysis. The upper limit of the forming force is greatly affected by the sheet thickness, and the lower limit is less affected by the sheet thickness. For an aluminium alloy sheet with a wall thickness of 1.5–3 mm, the upper limit value of the forming force for a single head changes linearly from 6.3 to 12.6 kN, and the lower limit value of the forming force for a single head changes linearly from 0.5 to 1 kN.

Author contribution The main processing experiment, conception and design of the study, and the preparation of the original manuscript were performed by BJ. WW was responsible for reviewing and supervising the final version. GC was responsible for editing and revising the manuscript. Measurement experiments and analysis were completed by YS and YG.

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Data availability The datasets used or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate All authors have approved to participate.

Consent for publication The manuscript is approved by all authors for publication.

Competing interests The authors declare no competing interests.

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