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ORIGINAL ARTICLE

Principles and apparatus of multi-point forming for sheet metal

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Abstract As a flexible forming method for sheet metal part, multi-point forming (MPF) technology is discussed in the paper. It employs two reconfigurable element groups to approximate the continuous upper and lower solid dies. With the technique, rapid fabrication of 3D sheet metal part is realized. The principles of multi-point die forming (MPDF) and multi-point press forming (MPPF) are described and then the rules to determine the size of the element are given. For any spatial shape surface to be formed, all elements' height can be calculated through the contacting point calculation equation. On the computer control, the shape of the two element groups can be adjusted by serial adjusting mode or parallel adjusting mode. MPDF apparatus that includes CAD software, computer control system, two element groups, hydraulic press and laser CMM is developed. Following the given MPF procedure, 3D sheet metal part was formed without failure. Due to the rapid change characteristics of the two element groups, several special MPF forming techniques that are impossible in conventional sheet forming have been investigated in detail. By flexible blank holder technique, thin sheet MPDF is realized. With sectional MPF, large size sheet would be formed on small scale MPF apparatus. Through closed loop MPF, spring-back would be compensated cycle by cycle, and large deformation part is obtained with incremental MPDF successfully.

Keywords CAD/CAM · Flexible manufacturing · Multi-point forming · Sheet metal forming

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1 Introduction

Three-dimensional sheet metal parts are widely used in various fields because of their advantages of light weight and versatile shape. The conventional forming method requires the matched solid die set, which results in considerable time and cost wasting in the production of the dies and long lead time of the products. In the field of shipbuilding, a large size steel plate is still bent by the line heating method in which the forming quality and geometrical precision depend mainly on the workers' experiences. A so-called multi-point forming (MPF) technology that combines reconfigurable dies with computer technology emerges as a better solution. The idea of discrete-pin die that was used for forming sheet metal was first introduced about 40 years ago. Nakajima established an automatically reconfigurable discrete die that used a positioning stylus mounted to the headstock of a NC milling machine to position the matrix of round pins [1]. After each pin's position was set, the entire pin matrix was clamped from outside, and functioned as a solid die. The apparatus could not be applied since the push of one pin makes adjacent pins move with it. After the 1980s, research to reconfigurable tooling for flexible fabrication was proposed by Hardt of Massachusetts Institute of Technology [2, 3]. He built a prototype in which the discrete-pin dies was set to a desired shape on the control of a NC system, clamped into a rigid tool, and served as a solid die set. A closed loop shape control methodology was also proposed [4]. In 1999, a full size reconfigurable tool for aircraft skin panel stretch forming was developed by MIT, Grumman Aerospace and Cyril Bath Company. The apparatus could not be used in stamping but only in stretch forming because there was only one side of the reconfigurable die. Inspired by Nakajima and Hardt, Finckenstein and Kleiner developed a experiment apparatus [5]. The numerically controlled tool system set a matrix of threaded rods to the designed shape and then the matrix of threaded rod transferred the shape to a discrete die. The configured discrete die was removed from the setting machine, clamped into a rigid stretch forming tool. In Japan, Nomoto in Tokyo University and Iseki in Tokyo Institute of Technology conduct research on sheet metal flexible forming with discrete pin dies. Li has engaged in sheet metal MPF for more than ten years in China. He called such technique MPF and proposed some new techniques such as multi-point press forming, sectional MPF, iterative MPF [6–8]. Most importantly, several commercial MPF presses on which rapid, cost-effective stamping for sheet metal parts can be realized have been developed. They have been successfully used in the forming of high-speed train body panel, ship hull plate, cranial titanium mesh prosthesis, etc. Recently, MPF press was applied to the forming of irregularly angled metal girders in the building of the Chinese National Stadium that will be the main stadium for Beijing 2008 Olympic Games.

This paper will introduce the basic principles of MPF and discuss some key techniques for industrial application based on past research work [9–14]. The rest of the paper is organized as follows: Section 2 describes MPF principles. Section 3 analyzes the adjusting mode of the two element groups and introduces the MPDF apparatus. Section 4 addresses MPDF working procedure and the measures to prevent forming defects. Section 5 investigates some key MPF techniques to improve forming quality. Finally, concluding remarks are given in Section 6.

2 Multi-point forming principles

2.1 Multi-point forming

In MPF, the solid stamping dies are replaced by two sets of reconfigurable “element groups”, as shown in Fig. 1. For each element, it can be numerically controlled to its desired height to approximate a continuous 3D tooling shape. So, as a universal tool, the upper and lower element groups are applied in the forming of sheet metal to replace solid dies.

In MPF operation, each element’s height can be adjusted rapidly. Before forming, the two element groups are set to the desired shapes according to the CAD data. There is no relative movement between adjacent elements during forming. The functions of upper and lower element groups are the same as solid dies. This representative method is defined as multi-point die forming (MPDF). While in another method, all elements are not adjusted in advance but kept at the same height. During forming, they are controlled to reach desired heights with appropriate speeds, the sheet metal which is clamped between the upper and lower element groups is forced to generate plastic deformation. There is relative movement between the adjacent elements and each pair of element functions like a small press. So it is called multi-point press forming (MPPF).

2.2 Forming capability of the element group

Spatial 3D sheet metal parts need to be formed with two discrete element groups in MPF. Shape surface in this paper is defined as the surface contour of the element group expressed as a height matrix. With equations in [12], the two height matrixes can be calculated easily. In order to determine the forming capability of the element groups, theory in signal processing is applied here. Firstly, two hypotheses are introduced.

Smoothness assumption The part shape that will be formed with MPF has sufficient smoothness such that the high spatial frequency components (short wavelength component such as surface roughness and waviness) are small and can be ignored.

Height field assumption The design shape, formed part shape can also be represented as a height field function $f(x,y)$ defined in the 2D domain, which is the same as the shape of the element group.

By sampling the spatial surface $f(x,y)$, the shape surface in MPF can be expressed with Eq. (1):

$$f_d(m,n) = f(x,y)comb(x,y) \tag{1}$$

$$comb(x,y) = \sum_{m=1}^{M}\sum_{n=1}^{N}\delta(x - m\Delta x,\ y - n\Delta y) \tag{2}$$

$f_d(m,n)$ is the surface discrete expression. M and N are element numbers in x,y direction, respectively. Δx and Δy are the centre distances between two adjacent elements in x, y direction, respectively (i.e. the cross section size of the element, let $\delta=\Delta x=\Delta y$ in MPF).

Fig. 1 The two reconfigurable element groups

To recover the undistorted surface $f(x,y)$from $f_d(m,n)$ in the signal processing field, the Nyquist frequency must be less than one half of the sampling frequency. In a similar way, if the highest spatial frequency component f_c satisfies equation (3), a compliant part will be formed with the element groups properly.

$$f_c \leq 1/2\delta \ or \ \delta \leq 1/2f_c \tag{3}$$

Equation (3) shows that, if the size of the element is δ, the highest spatial frequency component that determines the geometry of the part to be formed is limited. It means that the forming capability in geometry of the size of elements is determined and the size of the element can be designed based on the highest spatial frequency component of the part.

On the other hand, the maximum part size depends on the number of elements, and the maximum sheet thickness on the elements' load carrying capacity.

3 Design and analysis of MPF apparatus

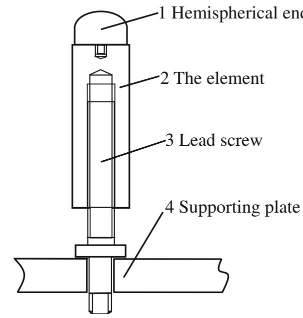
In MPPF, the heights of all elements need to be controlled dynamically and simultaneously. At the same time, their control speeds should be controlled carefully as well. It is difficult because the forming process is done under varying deformation loads. While in MPDF, only the elements' heights need to be controlled before forming. With the MPDF method, several laboratory-scale and production-scale apparatus have been developed.

3.1 Element group design and shape adjusting mode

Height adjustment for each element can be realized by different ways, such as servo-controlled hydraulic cylinder and numerical controlled lead screw. For MPDF, lead screw is a cost-effective way. The element is designed as Fig. 2. Part 1 is the hemispherical forming end that can keep point contact with any 3D spatial shape surface. To avoid golf ball-like dimpling defects, there is a polyurethane cap on the tip sometime. Part 2 is the hollow element with internal thread supported on a self locking lead screw 3. By driving the lead screw into the bottom of the hollow element, its height can be adjusted easily. All elements are square in cross section and equal in length. They are densely arranged into a matrix (as shown in Fig. 1). The vertical load can be supported by the bottom plate 4, while side forces on each element could be transmitted to the side supporting plates and supported by them. When all elements are set to the desired heights according to CAD data, they will function as solid dies.

The element group can be set in serial adjusting mode (SAM) or parallel adjusting mode (PAM). In SAM,

Fig. 2 Structure chart of the element



elements are adjusted one by one or several by several via a robotic device. The robotic device includes a numerical controlled (NC) $x-y$ platform that can move along x and y direction precisely and L sets of NC z axis adjusting heads that are fixed on the platform. When the platform moves to a position, L elements can be adjusted to their desired heights simultaneously. For a $m \times n$ element group, the total set-up time T_{total} satisfies the following equation:

$$T_{total} = \sum_{i=1}^{P} \left(T_i^M + T_i^Z \right), \tag{4}$$

where $P = m \times n/L$, T_i^M is the time cost on platform movement from position i to position $i+1$. $T_i^z$is the maximum height adjustment time for the L elements.

In Eq. (4), the total set-up time increases with the increase of element number, but the SAM control cost is kept low. It satisfies Eq. (5).

$$C_{total} = 2 \times \left(C_x + C_y + L \times C_z \right) \tag{5}$$

where C_x, C_y, C_z is respective single axis control cost of x,y,z.

While in PAM, all elements can be adjusted simultaneously, because each element has its respective numerical control and drive unit. So the shape contour of the element groups can be reconfigured rapidly. The unit includes motor, gear box, rotary encoder and a control circuit board. The control circuit has functions such as communication with host computer, closed-loop position control for the motor, element's height and running status storage, etc. When it receives running commands from the host computer via the industrial field bus, it controls the motor to adjust its element to the desired height independently and feedbacks the element status to the host computer. All control and drive units have the same dimensions and functions but different address codes. When the number of element increases, the total set-up time T_{total} remains unchanged and is equal to the maximum adjustment time of one element in PAM, but the control cost increases with the increase of elements.

$$C_{total} = 2 \times m \times n \times C_{one}, \tag{6}$$

where C_{one} is the control cost for one control and drive unit.

For a MPDF apparatus, the choice of the shape adjustment mode depends on the optimized result between the set-up time and control cost in MPF apparatus design.

3.2 MPDF system

As a rapid forming apparatus, MPDF systems have been developed for different applications. As shown in Fig. 3, it is mainly composed of CAD integrated software sub-system (CADS), computer control sub-system (CCS), the upper and lower element groups (also called multi-point dies), and hydraulic press. Laser CMM is an optional device used to measure the 3D shape of the formed part. The whole process from shape design to part formation is carried out on the same system.

3.3 CADS

CADS is a CAD/CAM integrated software developed with VISUAL C++6.0 under the WINDOWS platform. It is for the design of the element group shape, selection of forming method, calculation of the height matrixes and simulation of the forming process. With the GUI interface, 3D shape can be constructed based on the inputs, including four boundary curves, a series of points and/or a series of cross section curve. CADS can also accept the standard data files from other commercial CAD software. With 3D shape data $P(x,y)$, the shape contour of the two element groups, i.e. two height matrixes $D^U(m,n)$ and $D^L(m,n)$ are calculated after the MPF method is chosen and the workpiece forming position is determined. If necessary, FEM simulation and inspection of the contacting conditions between the elements and sheet may be done. If there is no fault, the two height matrixes are transferred to the CCS.

3.4 CCS

For SAD, CCS is a typical multi-axes numerical control system. When it receives data from CADS, the host computer, which is an industrial workstation, translates data to control codes. Through digital AC servo motors, it controls the upper and lower sets of robotic device to adjust the elements. When finished, the element groups are used to form metal sheets with the hydraulic press. However for PAD, CCS is quite different. It is an integrated computer control system. The host computer has functions such as exchanging data with CADS, setting and changing the forming and controlling parameters, communicating with slave control units that are distributed in apparatus via industrial field bus, adjusting the shape contour of the element groups, data saving, equipment testing and protection, etc.

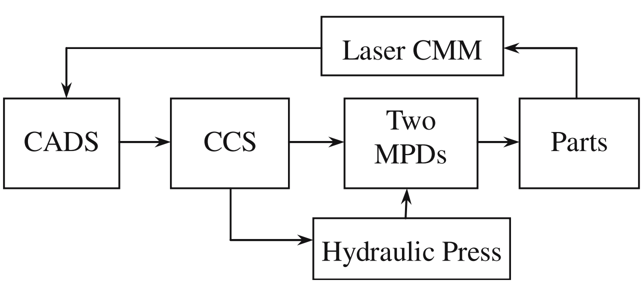


Fig. 3 Flow chart of MPDF system

4 MPDF for sheet metal parts

4.1 Zero-adjustment of the element groups

After the MPDF apparatus is installed for the first time or at some cases, the height of each element is different. All of them should be adjusted to the same level that is set as the reference level $D_{zero}(m,n)$. As show in Fig. 4, when a height calibrator is put between the upper and lower two rows, the elements in the two rows can be automatically adjusted to the zero position under the control of CCS. When all the elements are set to the zero position, the height data are stored in computer as the reference level $D_{zero}(m,n)$. Any other shape contour of the two element groups can be obtained by adjusting each element's height based on this reference level.

4.2 Operation procedure of MPDF

The general MPDF process includes the following steps:

Step 1: Input the design data, the CADS will generate a CAD model $P(x,y)$ automatically.
Step 2: Choose the MPDF technique.
Step 3: Set the forming parameters and determine the forming position on computer.

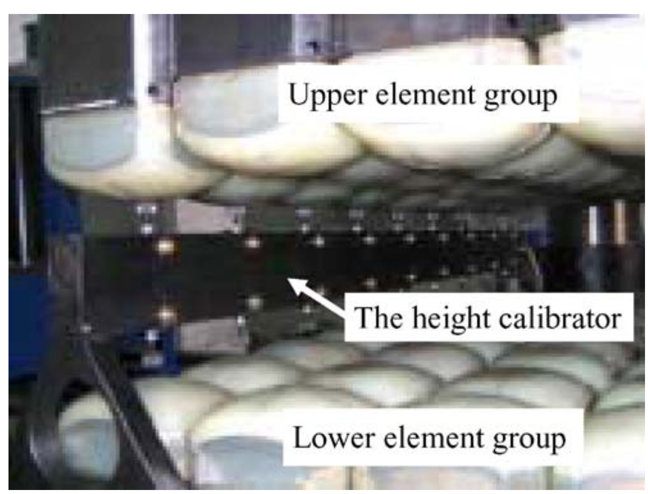


Fig. 4 Element group initialization

Step 4: Conduct technique computation, and obtain the two height matrixes $D^U(m,n)$ and $D^L(m,n)$.
Step 5: Inspect data. If no mistake, they transmitted to CCS; otherwise, go to step 3.
Step 6: CCS receives the data, which will be translated to control codes.
Step 7: All elements are set to the desired heights by CCS, that is, the two element groups are set to the desired shape.
Step 8: Align blank sheet between the element groups, form the plate with hydraulic press.
Step 9: Measure the formed part. If it is acceptable, end the process. If the shape is not identical to the designed shape, it will be reformed with the amended shape contour of the element groups.

4.3 Dimpling suppression

To produce high quality parts with a smooth surface, measures to prevent defects such as dimpling and wrinkling must be taken. In MPDF flat sheet and elements' hemispheric end contact at a point first. With the load increasing, plastic deformation occurs at the contact zone. Therefore the concentrated stress results in dimpling. Also, because the contact zone between the workpiece and elements is a series of points, less constrain causes wrinkling on a non-contact zone. By using deformable elastic pad, defects can be prevented effectively. The sheet is sandwiched between the two elastic pads. They are put between the upper and lower element groups and formed together. It obviously avoids dimpling during forming via distributing the centralized load to the whole sheet. While wrinkling chance is reduced due to the increase of contacting area as well as the enhancement of constrain on sheet. The elastic pad can be made of certain synthetic rubber-the polyurethanes. Due to the outstanding abrasion resistance, toughness, it can be used many times. It also may be made of spring steel strips.

5 Special MPDF techniques

5.1 Thin sheet metal MPDF with flexible blank holder

MPDF has been successfully used in the forming of medium thickness sheet metal parts. However, for thin sheet metal used in the fields such as automotive industry, MPDF encountered many difficulties. When constraints on the sheet are not enough, MPDF has a tendency to buckle under the influence of the tangential compressive stresses because its moment of inertia in buckling is small. To prevent wrinkle formation one flexible blank holder technique was proposed. Figure 5 is a MPDF apparatus developed for thin sheet metal forming. Each side of element group comprises 40×32 elements and each element's cross section area is only 10×10 mm. At the four sides of the element group, there are 40 hydraulic cylinders. Before MPDF, the sheet is clamped between the upper and lower cylinders first with the pressure set by the control panel. During forming, their heights change with the change of the workpiece, but the pressure is kept constant. With this flexible blank holder technique, MPDF experiments with 0.5 mm thickness 08AL sheet metal used in car body panels has been done. Figure 5 is a human face shape part.

5.2 Sectional MPDF

Usually the sheet size is smaller than the solid die in stamping, but in shipbuilding yard, the plate size may reach several ten square meters and thus it is difficult to use the stamping method. In MPDF, this kind of large size part can be formed section by section instead of cutting it into many pieces because the shape contours of the two element groups can be changed rapidly. This is sectional MPDF technique with which large size or large deformation plate is formed continuously on small scale MPDF apparatus. It includes one direction sectional MPDF and bi-direction sectional MPDF. Research shows that compared with general MPDF, there are three different zones: free zone $P^i{}_{free}$, forming zone $P^i{}_{forming}$ and transition zone $P^i{}_{trans}$ on one sheet during the ith forming operation. In the transient zone, useless localized deformation occurs because of the influence of forming zone and free zone. Simple 2D sheet forming (such as cylinder shape) becomes complex 3D sheet metal forming. As a result, the shape contour of the element group is divided into two regions: forming region $D^{i+1}_{for\min g}$ and transition region D^{i+1}_{trans}. The shape design for

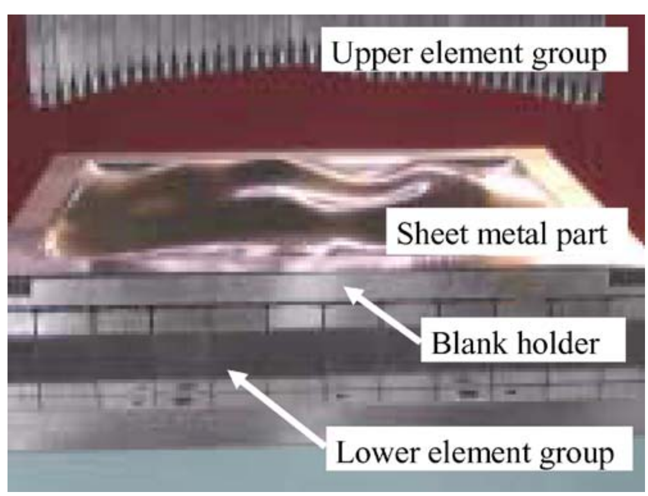


Fig. 5 Thin sheet metal MPDF

the forming region is usually conducted according to the target shape. However, the design for the transition region is more complicated. The part shape formed with such regions is not the objective shape and must be reformed. So the element group shape design for the transition region plays a key role in sectional MPDF. It aims at making the sheet deformation uniform in the transition zone. If the design shape is not appropriate, that will lead to forming defects such as wrinkling, localized over-forming, even cracking. The NURBS method and other optimization methods are usually adopted for the transition region design. With it the shape surface of the transition region D^{i+1}_{trans} used in the next section forming is constructed to ensure sufficient smoothness from the forming zone's edge cross section line to the cross section line of the unformed zone. So the entire shape of element group satisfies Eq. (7).

$$D^{i+1} = D^{i+1}_{trans} + D^{i+1}_{for\min g} \tag{7}$$

During the sectional MPDF operation, when the numbers of the section are determined, marks should be made on the blank plate under the guide of the CAD software to ensure the part alignment and position. After one section is formed, then the adjacent one is the next. Figure 6 shows a sectional MPDF operation process. The apparatus was developed for large size plate forming. It has 81×2 elements and working area of 1350 ×1350 mm, but the formed plate size with sectional MPDF reaches 1200 × 6000 mm with thickness range from 10 to 70 mm.

5.3 Closed-loop MPDF

Spring-back, the elastic recovery of a sheet after it is unloaded, causes the deformed part to deviate from the desired shape. Though spring-back coefficient can be set in the shape design of the element groups, forming error still exists. In the MPDF process, variables that affect the spring-back include variations both in the material and process parameters. If all variables are considered as system disturbances, the MPDF process is simplified to be a single input and a single output system (SISO), $Y=f(U)$. To eliminate spring-back, a closed-loop control method was proposed due to the rapid changing characteristic of the lower and upper element groups. After one forming cycle, although the formed part shape is not identical to the designed shape, it is measured and reformed with the modified element group's shape contour. With this technique, compensating for spring-back will be done cycle by cycle.

During the closed-loop forming process, both input and output are spatial shapes, the key technique is how to predict the next shapes of two element groups according to the designed shape and feedback shape. The transfer function of the forming process is defined as Eq. (8):

$$H_i(u,v) = (P_i(u,v) - P_{i-1}(u,v))/(D_i(u,v) - D_{i-1}(u,v)) \tag{8}$$

where $P(u,v)$ and $D(u,v)$ are discrete Fourier transform (DFT) of the formed part $P(m,n)$ and the element group shape $D(m,n)$. The incremental form of Eq. (8) between two forming cycle is as follows:

$$D_{i+1} = D_i + KE_iH_i^{-1} \tag{9}$$

where $E_i = P_{obj} - P_i$, P_{obj} is the design shape. K is a gain factor. By identifying $H_i(u,v)$ with non-parameter model identification methodology, the next DFT shape of the element groups will be predicted. Through inverse DFT, the two height matrixes of the element groups are predicted. The part will be formed again to reduce the shape error. After several cycles, the formed part shape error decreases into an acceptable range.

In Eq. (9), k is a factor. If it is less than one in each closed-loop forming cycle, the part deformation in each step stays small. As shown in curve 1 of Fig. 7, the accumulated deformation of the part reaches the objective

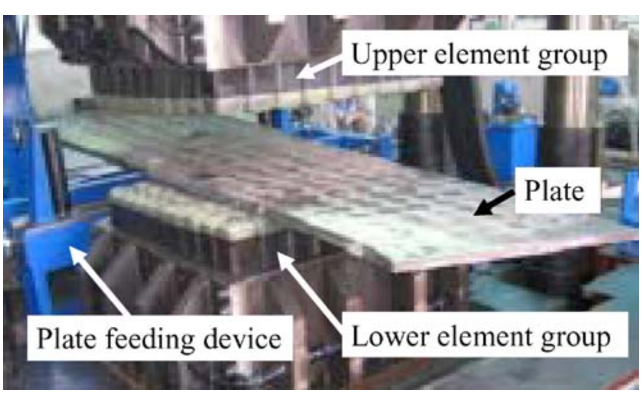


Fig. 6 Sectional MPDF operation

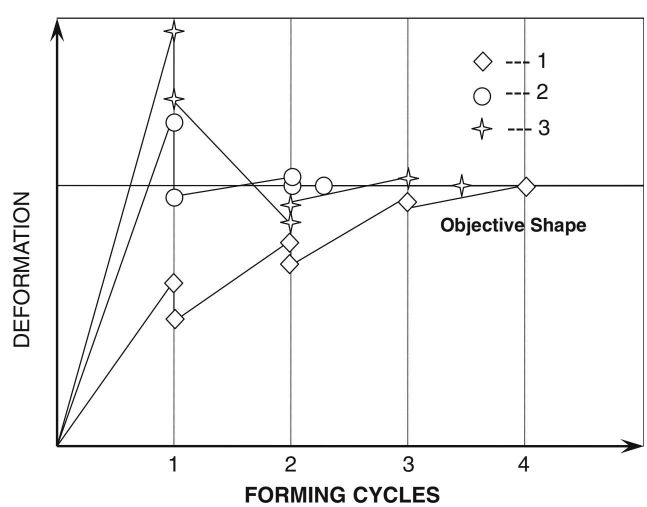


Fig. 7 Different closed-loop MPF techniques

value (i.e. large deformation workpiece is obtained) after several forming steps. The technique is called incremental MPDF with which large deformation can be reached without failure.

If k is larger than one, the workpiece will be over formed based on the first forming cycle. When unloaded, the workpiece deformation is still larger than the objective value. In the second step, the workpiece is formed to the opposite direction, and then over formed again, after three or four steps, the workpiece reaches the design shape. This technique is called iterative MPF (as shown in curve 3 of Fig. 7). With this technique, the residual stress in the plate will be eliminated gradually. When unloaded, the final part is not deviated from the desired shape because of spring-back.

Certainly, if the factor is chosen appropriately, the workpiece can be formed to the designed shape in two or three cycles (as shown in curve 2 of Fig. 7). However, more forming cycles will lead to strain hardening, so it should be controlled carefully.

5.4 Reverse engineering in MPDF

As shown in Fig. 3, there is a laser scanning measurement machine in the MPDF system. It can be used in closed-loop MPDF to improve the forming precision. At the same time it can also be used in MPDF reverse engineering. After the geometric shape of a 3D sheet metal product is scanned, it will be reconstructed as the design CAD model. Through MPDF, a replica will be formed rapidly.

6 Remarks

The principles of MPPF and MPDF, design rules of the two element groups and adjustment modes were studied in this paper. The MPDF apparatuses were developed on which the rapid forming process from the shape design to get desired part formed, even though the shape rapid measurement, were accomplished. Because the shape of the element groups can be changed rapidly according to the CAD data, several special MPDF techniques such as flexible blank holder technique for thin sheet metal forming, sectional MPDF for large size sheet forming, closed loop MPDF for high precision forming and sheet metal MPDF reverse engineering were investigated in detail. With these techniques, special sheet forming operations that are impossible in conventional stamping have been realized. MPF is a rapid, digital and cost-effective forming technique for sheet metal parts. It will find extensive applications in sheet metal forming fields such as airplane skin panel, vehicle body skin panel, medical engineering, etc., and also in plate forming fields such as shipbuilding, pressure vessel, metal sculptures, modern architectures, etc. especially for small lot products.

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