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ORIGINAL ARTICLE

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# Generation and suppression of local severe plastic deformation in sectional multi-point forming

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**Abstract** Sectional multi-point forming (SMPF) technology provides a new solution for forming large-size sheet metal. With this technique, large-size parts of sheet metal can be manufactured on a smaller multi-point forming press. But the force status and deformation of the workpiece are complicated in SMPF; the local severe plastic deformation will be produced easily in the transition region, and strain-hardening will be commonly produced subsequently. The hardening is difficult to eliminate in subsequent processes, which will largely affect the final deformation quality. In this paper, the generation of local severe plastic deformation was discussed; NURBS-based modeling method was used to construct the shape of the assortative region to suppress the defect. Experiments proved that the method is fairly effective. Finally, a plan was suggested to raise further the forming limit of materials and enhance the work efficiency by combining multi-point press forming with assortative region method.

**Keywords** Sectional multi-point forming · Local severe plastic deformation · Assortative region method · Sheet forming

## 1 Introduction

Multi-point forming (MPF) [1–5] is a flexible manufacturing technique for the forming of three-dimensional surfaces of sheet metals. MPF is dividing the curved surface of the die into many discrete pins, using many punches instead of the traditional dies, and each punch can be controlled by computer so that the enveloping surface of punch group can be changed at any time. This way, the multi-point die (MPD),which is approximate to continuous forming surface of dies, can be used to carry out the forming of different curved surfaces in place of using many dies. This flexible feature is especially suited to sectional forming.

Sectional multi-point forming (sectional MPF or SMPF) [6] is a technology based on MPF (see Fig. 1). It takes full advantage of the MPF's feature that MPD can be varied easily during the forming process. In SMPF, a large-size sheet metal would be formed in a way section by section, and all sections don't need to be parted. After one section of the sheet was formed, MPD would be modified to form the other section in sequence with the sheet fed. This way, current presses can be utilized to form larger pieces of sheet metal, and the cost of new devices eliminated. In addition, much higher efficiency and precision can be attained in SMPF than traditional handwork forming. During SMPF, the whole mechanical performance of the part would stay in a good condition because all the sections don't need to be parted from each other and are cold-formed. Sectional multi-point forming technology offers a new choice for large-size sheet metal forming.

However, the force status and deformation of the workpiece in SMPF is much more complicated than whole MPF [6] and conventional die forming because of the interaction of forced deformed region and rigid region. The local severe plastic deformation easily occurs in the transition region. And its control is difficult. It extremely affects the final deformation quality.

In this paper, the deformation regions in SMPF are introduced briefly, and the generation of local severe plastic deformation in SMPF is analyzed in detail. Then the assortative region method based on NURBS is adopted to suppress local severe plastic deformation. Finally, to improve the force status of the workpiece and enhance the efficiency, multi-point press forming is applied with assortative region method together.

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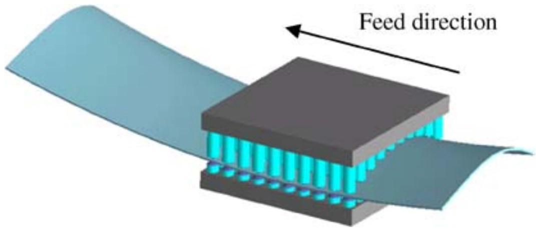



**Fig. 1** Sectional multi-point forming process

## 2 Deformation regions in SMPF

During the sectional multi-point forming process, the section of the part under pressure would change shape, but another not. So there must be a transitional region between both. Figure 2 shows the distributions of deformation region after the first pressing is finished.

In terms of forced status, three regions are included in sheet metal: the forced deformed region (deformed and forced by the press), the free deformed region (deformed but not forced) and the undeformed region.

In terms of the deformation effect, the sheet metal can also be divided into three basic regions: the effective deformed region (deformed and accords with object shape), the transition region (deformed but doesn't accord with object shape), and the rigid region (undeformed).

The transition region is composed of the free deformed region and a part of the forced deformed region. It plays a very important role in SMPF. In the transition region, the area contacted with MPD will not achieve an ideal shape due to the affection of unforced region. The area is called the inadequate deformed region, which is the intersectant area of the forced deformed region and the transition region. The detailed explanations can be found in [6].

At present, the main problem in SMPF is the local severe plastic deformation [7] produced near the intersect line between the forced and the free deformed region in transition region. Compared with whole MPF, it is a particular defect. And a lot of experiments showed that it almost emerges in SMPF. Even when the object shape is a simple two-dimensional deformation, such as a cylinder, local severe plastic deformation also emerges on the final part surface (Fig. 3). Besides, the local severe plastic deformation usually causes strain-hardening. The hardening is difficult to eliminate in subsequent processes so the final deformation quality is greatly affected. It extremely impedes the SMPF technology to be applied in practice. So, the generation and suppression of local severe plastic deformation will be studied in this paper.

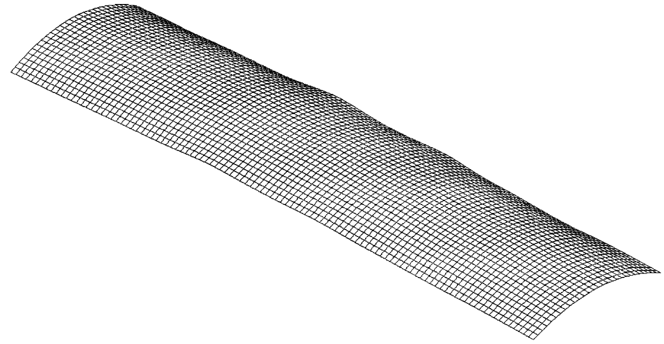


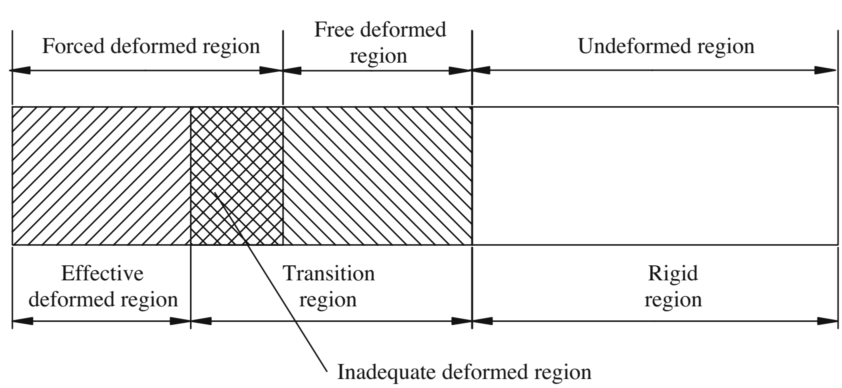
**Fig. 3** Cylinder workpiece with local severe plastic deformation after SMPF

## 3 Generation of local severe plastic deformation

A cylinder workpiece was selected as an example to study the generation of local severe plastic deformation. At first, the contact status of a row of punches and sheet metal on the transverse section of workpiece is analyzed in multi-point die forming (Fig. 4).

The sheet metal is in the state of four-point bending at the beginning of deformation (Fig. 4a). As the upper punches move down, the center of the sheet metal begins to produce local bending deformation firstly. As bending increases further, the sheet metal is in contact with four punches at the center of the upper punches. Thus, four-point bending turns to six-point bending (Fig. 4b). As the deformation continues, the sheet metal separates from inner two punches at the center; six-point bending turns to four-point bending again, but the contact points of the sheet metal and the upper punches have changed from the inner to the outer two punches at the center (Fig. 4c). At this time, the area from the contact points to the sheet metal longitudinal edge don't almost produce plastic deformation, this area is straight. During the forming process, the contact points of the sheet metal and upper punches continue to change, including the movement along the

**Fig. 2** Distribution of deformation regions



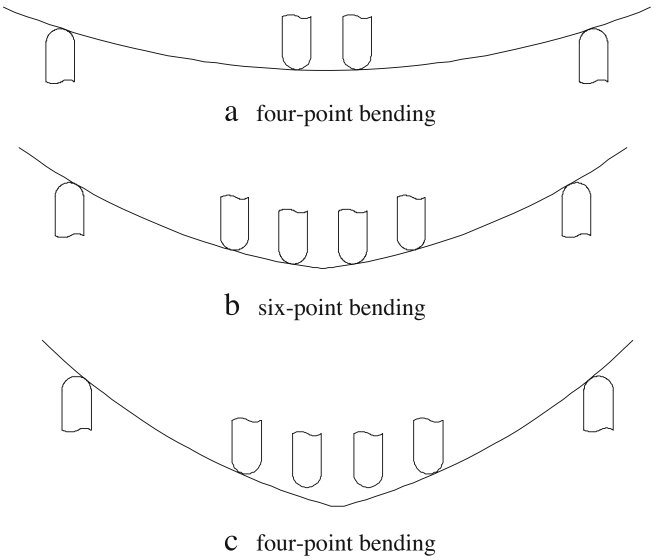



**Fig. 4** Multi-point die forming process. **a** Four-point bending. **b** Six-point bending. **c** Four-point bending

spherical surface of the single punch and the transfer between bunches. And, the force status of the sheet metal switches continuously between four-point and six-point bending. The deformation extends gradually to the longitudinal edge of the sheet metal until the it comes into contact with the lower punches, that is, contacting the bottom. Then, the contact point gradually increases until all the punches are in contact with the sheet metal. One thing here must be pointed out: Compared to conventional die forming [8], the phenomena of contacting bottom will not occur again after the first instance because there are spaces between all the punches. It is not good for the curvature uniform distribution of deformation results.

According to the description above, when a cylinder workpiece is formed, the center region of the sheet metal first comes into contact with the punches. Then the contact region gradually extends to the longitudinal edges. The longitudinal edges of the workpiece under pressure are in contact with the punches until the moulds are matched. Namely, the restraint is insufficient at the edges of the workpiece.

The workpiece is manufactured section by section during SMPF. This is different from the whole MPF and conventional die forming. The deformation of the forced deformed region is also influenced by the rigid region and the end of the forced region is close to the rigid region. At this position, the rigid region hinders the flow of metal; it leads to large local in-plane compressive stresses. At the same time, the compressive destabilization doesn't easily come forth at the center region on account of the normal restraint from punches. However, the normal restraint at the edges is so insufficient that the local severe plastic deformation concentrates at the longitudinal edges of cylinder workpiece near the intersect line between forced and free deformed region in transition region (Fig. 5).

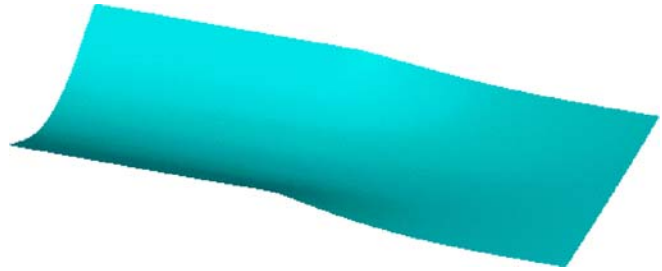


**Fig. 5** Shape of a cylinder workpiece after first press in SMPF

When the workpiece of another shape (such as spherical, saddle shape, and so on) is analyzed in sectional multi-point forming, similar results can be obtained. The local severe plastic deformation always exists near the intersect line between the forced and the free deformed region in the transition region, and concentrates at the position where the restraint is insufficient.

The formative mechanics of this kind of defect is the same as that of wrinkling, so it can be regarded as a type of wrinkle phenomenon.

In SMPF, even the object shape is simple 2D deformation (such as cylinder) the local severe plastic deformation will also be produced to affect extremely the final deformation quality. So it is necessary to adopt some methods to suppress the local severe plastic deformation.

## 4 The design of the assortative region

The assortative region method [6] is an effective method to suppress the local severe plastic deformation in SMPF. The key to this method is the design of the assortative region shape. Here, a method based on NURBS is presented to construct the surface of the assortative region. This method is simple; however, it has proven very effective in practice.

### 4.1 The assortative region method

The basic idea of the assortative region method is to design an assortative region between the forced deformed and the rigid regions by changing the object shape of the sheet metal in the transition region during pressing. The assortative region has an assortative action between the forced and unforced regions. An elaborately constructed shape of the assortative region will disperse the deformation concentrated near the intersect line between the forced and the free deformation regions. Compared to the multipass forming method [6], the efficiency of forming can be enhanced by the assortative region method and the forming limit of materials is higher through the assortative region method than the overlap region method [6].

The assortative region method [6] is the best way to suppress the local severe plastic deformation in SMPF. It is the key to making sectional forming technology applied in practice.

### 4.2 Design of the assortative region based on NURBS

The substance of the assortative region design is making the deformation in assortative region as uniform as possible. That can be abstracted to a mathematical problem of how to transit uniformly from the section curve of objective shape edge (usually a curve) to that of blank (usually a straight line) in the range of assortative region.

For one-way sectional deformation [6], if the section curve of blank is a straight line, the surface of the assortative region should at least have several geometric characteristics as:

1. The surface of the assortative region is smooth, and can't raise the tearing and wrinkling. In a mathematical sense, it suggests the surface of the whole assortative region should keep $C^2$ continuity at least.
2. The assortative region, the effective deformed region, and the rigid region should keep the position continuity. It requires the boundary line that connects the assortative region and the effective deformed region coincides with the corresponding boundary line of the effective deformed region, and the boundary line that connects the assortative region and the rigid region also coincides with the corresponding boundary line of rigid region.
3. The intersect line of the assortative region surface and the effective deformed region surface, and the intersect line of the assortative region surface and the rigid region surface should both reach to $G^1$ continuity. This means that two curved surfaces have a common tangent plane along the common boundary line.

There are many methods suited to the surface modeling of the assortative region. In this paper, the non-uniform rational B spline (NURBS) [9] method will be adopted since the range of curved surface expressed by NURBS method is broad, and the NURBS method can represent primary analytic and free-form surface uniformly. What is more, the NURBS method can be used to carry out shape controlling, shape modifying, and splicing between surfaces conveniently. In this application, bicubic non-uniform rational B spline [10] was used.

To bicubic non-uniform rational B spline surface, its surface is $C^2$ continuous, thus the first geometric characteristic is met. According to the second, two boundary lines of the assortative region surface can be determined. One boundary line always coincides with that of the effective deformed region, and another is a straight line, but we don't know the position of the straight line in height. When this straight line is determined, it is mainly considered that its position should make the deformation assortative amount as little as possible, and the deformation of the assortative region should be uniform. The following method can be adopted to determine the position of this straight line: Making a cross section at the center of each longitudinal row of punches (Fig. 6), and then making the tangent line of this section line at the edge of the effective deformation region, this tangent line intersects with the edge line of forced deformed region at the A1 point. The algebraic average value of the crossing points' heights of all rows is regarded as the height of this straight line, (see the position of "A" point as Fig. 6 shows). After two boundary lines of assortative region surface are determined, according to the first and the third geometric characteristic, a line is taken between two determined lines again, it is the fitting line through all the mid-points of lines that connect B and A of all rows (Fig. 6). When the three lines are regarded as the section lines of assortative region surface, the surface of the assortative region can be constructed by NURBS interpolating. Of course, to control the shape of the assortative region better, more intermediate lines can be taken, for example two or three, thus the assortative effect of deformation will be better.

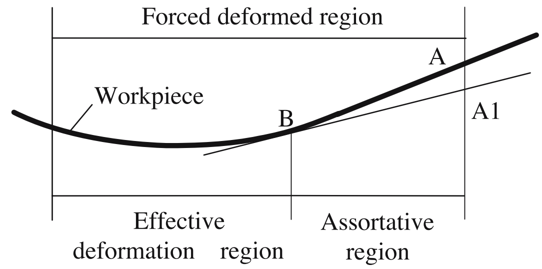



**Fig. 6** Determining a boundary line of assortative region surface

## 5 Results

An example of constructing the curved surface of the assortative region was given here, using the three section lines method mentioned above, and the comparison experiment was carried out to check the validity of the design method of assortative region presented in this paper.

The objective shape is saddle surface with two-direction curvature radius of 180 mm. Both blanks have the same original rectangular shape 280×140 mm, with a thickness of 3.0 mm, material of pure aluminum. Each of the matrices of punches used in the MPF press contains 10×10 punches, and the forming area of the MPF press is 140×140 mm. The assortative region contains four rows of punches.

The design result of the assortative region with three section lines is shown in Fig. 7. Figure 8 shows the results of forming with and without the assortative region in SMPF. The upper one is the result without the assortative region method. We can see there is wrinkling on the surface of the workpiece. The lower one is the result with the assortative region designed by the method mentioned above. The surface of the workpiece is smooth. It is obvious that the forming quality of the workpiece is enhanced significantly when the assortative region method is adopted. So, the design of assortative region based on NURBS is very effective in suppressing the local severe plastic deformation.

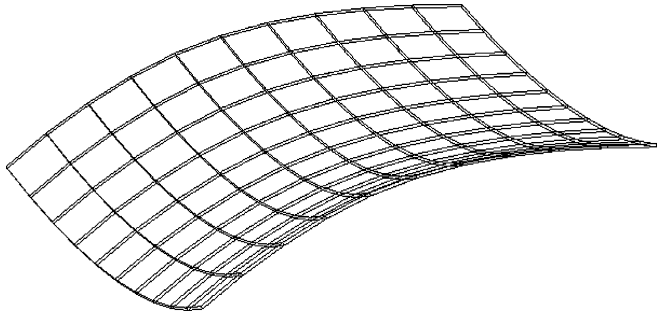


**Fig. 7** Design result of assortative region with three section lines

**Fig. 8** Results of forming with and without assortative region

## 6 The combination of two methods

According to the characteristic of multi-point forming technology, Professor Li MingZhe proposed four typical forming methods [1]. They are multi-point die forming, multi-point half die forming, multi-point press forming and multi-point half press forming. Of the four methods, multi-point press forming is the most ideal forming mode [11].

Multi-point press forming is made up of all active punches [1] (upper and lower). They can be adjusted to the proper position during the process, not before the process, to form the necessary shape of the products. There is relative movement between the punches, and each pair of punches act like a small press, so it can be called multi-point press forming. This method can fully show the flexible characteristic.

In multi-point die forming, when the curvature of the workpiece is too large, even when the assortative region method is used, the local severe plastic deformation will still generate in transition region because the rigid region strongly suppresses the deformation of forced deformed region. If multi-point press forming is applied to combine with assortative region method based on NURBS, the forming limit of materials will be enhanced further. In multi-point press forming, from the beginning to the end of forming, all punches (upper and lower) and sheet metal are in contact, namely, the punches always hold the sheet metal to form, which can avoid destabilization produced by insufficient restraint. Moreover, we can realize the best deformation by changing the deforming path [12] freely. In addition, compared with multi-point die forming, when multi-point press forming mode is used, the area of assortative region can be properly reduced and the same effect is kept, thus the efficiency of work will be enhanced.

## 7 Conclusions

(1) The local severe plastic deformation is the main defect in SMPF. In substance, it is a type of wrinkle phenomenon.
(2) In SMPF, the local severe plastic deformation always occurs near the intersect line between the forced and free deformed regions in the transition region, and concentrates at the position where the restraint is insufficient.
(3) The design method of the assortative region based on NURBS has been presented in this paper. The experiments proved that this method is convenient and effective.
(4) This paper suggests a plan of combining multi-point press forming with assortative region method to raise the forming limit of materials further and enhance the work efficiency.

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## References

1. Li MZ, Nakamura K, Watanabe S (1992) Study of the basic principles (1st report: Research on Multi-point forming for sheet metal). Proc of the Japanese Spring Conf for Technology of Plasticity 519–522 (in Japanese)
2. Li MZ, Nakamura K (1992) Harmful phenomena in multi-point forming (3rd report: Research on multi-point forming for sheet metal). Proc of the 43rd Japanese Joint Conf for Technology of Plasticity 425–428 (in Japanese)
3. Li Mingzhe, Liu Yuhong (1999) Multi-point forming: a flexible manufacturing method for a 3D surface sheet. J Mater Process Technol 87:277–280
4. Hardt DE, Gossard DC (1980) A variable geometry die for sheet metal forming: machine design and control. Proc of the Joint Automatic Control Conference, San Francisco, Aug
5. Hardt DE et al (1981) Sheet metal forming with discrete die surface. Proc 9th NAMRC 140–144
6. Chen Jianjun (2005) Sectional multi-point forming technology for large size sheet metal. Int J Adv Manuf Technol 25:935–939
7. Chen Jianjun (2001) The Study of Multi-Point Forming CAD and Sectional Multi-Point Forming Process. PhD dissertation of Jilin University, China

8. Yu TC, Zhang LZ (1992) Theory of plastic bending and its application. Science Press, China
9. Shi FZ (1994) Computer aided geometric design and non-uniform rational B spline (CAGD & NURBS). Beijing Aerospace University Press, China, pp 405–465
10. Tiller W (1983) Rational B-splines for curves and surfaces representation. IEEE CG & A 9(1):61–69
11. Cai ZY, Li MZ (2002) Multi-point forming of three- dimensional sheet metal and the control of the forming process. Int J Press Vessels Piping 79:289–296
12. Cai ZY, Li MZ (2001) Optimum path forming technique for sheet metal and its realization in multi-point forming. J Mater Process Technol 110:136–141