General Step Reduction and Enlargement Method for Knowledge-Based Process Planning of Totally Non-axisymmetric Forged Products with Blanking and Punching

Masanobu Umeda, Yuji Mure, Keiichi Katamine, and Kazuya Matsunaga

Abstract A forging process planning method, including blanking and punching, termed General Step Reduction and Enlargement (GeneSteR+E), is discussed for cold- and warm-forged products. It is applicable to non-axisymmetric forged products that consist totally of non-axisymmetric shape elements and can generate multiple process plans without relying on design cases. The shape of a forged product is split into outer and inner shapes, which are then split into axisymmetric and non-axisymmetric shape representation units termed basic elements (BEs) according to shape separation rules. Process plans are generated in reverse order from a final forged product by applying shape transformation rules that reduce the number of steps between BEs until a billet (or a blank) is obtained. The shape transformation rules are defined not only for forging, but also blanking and punching. An experimental knowledge base was implemented and applied to several non-axisymmetric forged products, such as an electrical connector. The results show that the GeneSteR+E method is applicable to the design of forging processes including blanking and punching of totally non-axisymmetric products and can generate satisfactory process plans comparable to those developed by an experienced engineer.

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1 Introduction

Process planning for cold- and warm-forged products involves generating a process to form a final product from a billet (or a blank) using forging dies. It significantly affects the quality, cost, and delivery of the forged products. The planning is time-consuming and difficult, even for experienced engineers, because extensive knowledge and experience in plastic forming, forging, blanking, and punching are required. Improvements in the efficiency and quality of the process planning are thus important issues in the design and manufacturing of forged products.

Traditional rule-based approaches [1, 2, 4, 6, 7, 11] and case-based approaches [3, 5, 8] have been proposed for forging process planning. Most are limited to products similar to design cases or are mainly axisymmetric products. In contrast, the General Step Reduction (GeneSteR) method [9] for forging processes does not rely on design cases and is applicable to non-axisymmetric cold- and warm-forged products, such as hexagon-head bolts and universal joint yokes, that consist of axisymmetric and non-axisymmetric shape elements. However, the GeneSteR method is still limited to partially non-axisymmetric forged products that contain axisymmetric shape elements and is not applicable to totally non-axisymmetric products that consist of only non-axisymmetric shape elements.

In this paper, an extension of the GeneSteR method, termed General Step Reduction and Enlargement (GeneSteR+E), is shown to be applicable to totally non-axisymmetric cold- and warm-forged products, such as USB Type-C connectors, without losing GeneSteR generality. In addition, the GeneSteR+E method can support the process planning for blanking and punching, which are often used with forging. To clearly distinguish a non-axisymmetric forged product that consists of only non-axisymmetric shape elements from one that contains axisymmetric shape elements, this paper uses the terms 'totally' with respect to the former and 'partially' with respect to the latter.

The model representation of totally non-axisymmetric forged products in the GeneSteR+E method is described in Sect. 2. Essential ideas and details to generate process plans via the GeneSteR+E method are described in Sect. 3, and the design procedure for forging process plans is described in Sect. 4. The experimental results applied to several forged products using an experimental knowledge base that implements the GeneSteR+E method are shown in Sect. 5.

2 Model Representation of Forged Products

2.1 Basic Representation Unit of Forged Products

The GeneSteR+E method represents the shape of a forged product using basic shape representation units termed basic elements (BEs), as in the GeneSteR method.

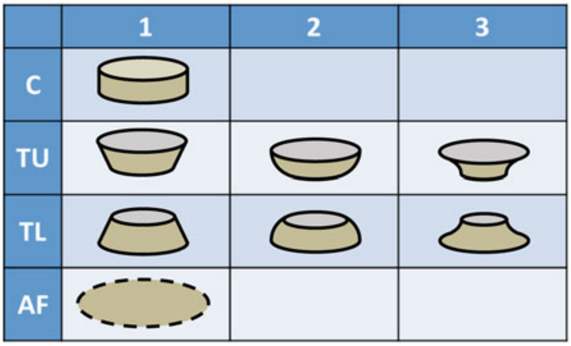
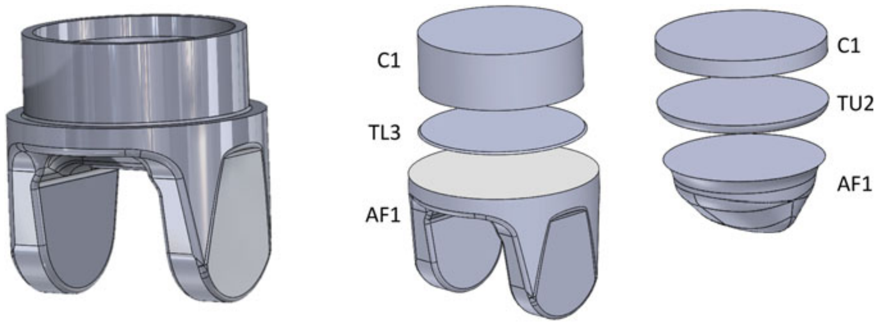


Fig. 1 Basic elements (BEs) for representing the shape of a forged product using shape representation unitsd. (Color figure online)



(a) A universal joint yoke

(b) BEs in the outer shape of a yoke

(c) BEs in the inner shape of a yoke

Fig. 2 Example of a partially non-axisymmetric universal joint yoke and its shape representations using BEs in the GeneSteR method. (Color figure online)

Figure 1 lists BEs, where row C and column 1 in the table is denoted C1. C2 defined in [9] was removed because it can be represented by using the pair TU2 and TL2.

Seven of the BEs, such as C1, have strictly defined axisymmetric shapes, such as a cylinder, whereas AF1 has no strictly defined shape and represents any non-axisymmetric shape. BEs have attributes characterizing their geometric outlines, with precise shapes specified by three-dimensional geometric models of a computer-aided design system.

The shape of a forged product is split into outer and inner shapes, which are then split into BEs by vertical planes to a forming direction. The design object model of a forged product represents its outer and inner shapes using two respective series of BEs. Figure 2 is an example of a universal joint yoke, that is partially non-axisymmetric, and its shape representations using BEs. In the GeneSteR method, successive non-axisymmetric shape elements in a forged product are represented using a single non-axisymmetric AF1.

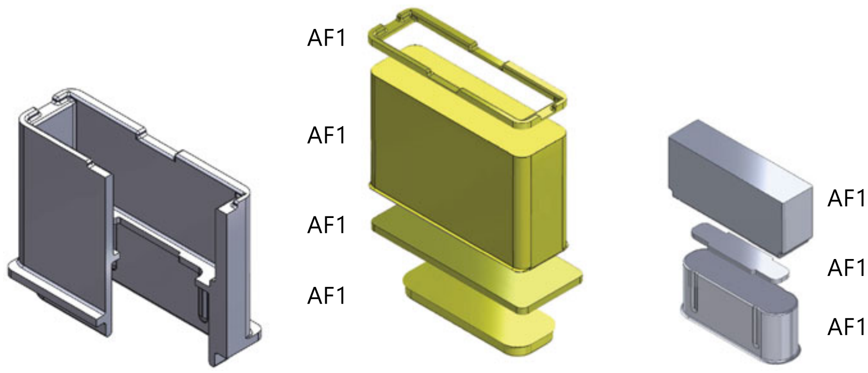
2.2 *Representation of Totally Non-Axisymmetric Forged Products*

The GeneSteR method represents successive non-axisymmetric shape elements using a single AF1. Therefore, a totally non-axisymmetric forged product, such as an electrical connector shown in Fig. 3a, that contains no axisymmetric shape elements, is represented with a single AF1. In such a case, a process plan that consists of only a single forming step is generated, as described in Sect. 3.1, and is generally unrealistic due to design constraints, such as the limit of the forming load.

The GeneSteR+E method introduces new shape separation rules (SRs) to split successive non-axisymmetric shape elements of a forged product into several non-axisymmetric AF1s. The SRs are as follows:

SR1 A plane splitting a forged product must be vertical to a forming direction.
SR2 A plane must split a forged product into exactly two parts.
SR3 A plane must be located at inflection points of the second-order differential function of a cross section.
SR4 A plane must be located at discontinuous points of a cross section function.

Rule SR2 prevents a BE from being separated into isolated parts, as in the universal joint yoke that has a projecting joint structure at the bottom. The shape separation is essential for the process planning of a totally non-axisymmetric forged product like the electrical connector. Figure 3b, c, respectively, shows BEs of the outer and inner shapes of the connector.



(a) An electrical connector

(b) BEs in the outer shape of an electrical connector

(c) BEs in the inner shape of an electrical connector

Fig. 3 A totally non-axisymmetric electrical connector and its outer and inner shape representations using BEs. (Color figure online)

3 General Step Reduction and Enlargement Method

3.1 Process Plan Generation by Step Reduction

As in the GeneSteR method, forged products, billets, and intermediate forged products in a GeneSteR+E process plan are all represented by BEs. Reversed forging process plans are generated by reducing the number of steps between successive BEs until a cylindrical or square billet is obtained. Step reduction is performed by simple step-by-step shape transformations over the BEs. Figure 4 illustrates a shape transformation and its corresponding forming step as the reverse operation of the shape transformation.

A forging process plan is generated by the following procedure. Starting from the forged product, one of the BEs of a post-formed product is selected as a key, indicated in red in Fig. 4. Then, one of the applicable shape transformation rules described in Sect. 3.2 is applied to the key. Several BEs are then selected as targets, which are indicated in blue in Fig. 4, according to an applied rule. The shape of a pre-formed product is created by substituting targets of a post-formed product with new BEs according to an applied rule. Because there are many candidates for a key, an applicable shape transformation rule, and targets, multiple process plans can be generated by an exhaustive search for them. In other words, a process plan consisting of a single forming step is generated if a forged product is represented using a single AF1.

3.2 Shape Transformation Rules

The shape transformation from post-formed to pre-formed products occurs according to simple rules defined for the outer and inner shapes. Figures 5 and 6 illustrate the shape transformation rules for the outer and inner shapes, respectively, and are extensions of those defined in the GeneSteR method.

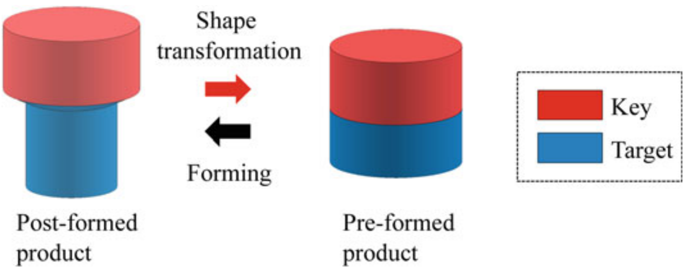


Fig. 4 Example of a shape transformation and the forming step of a process plan. (Color figure online)

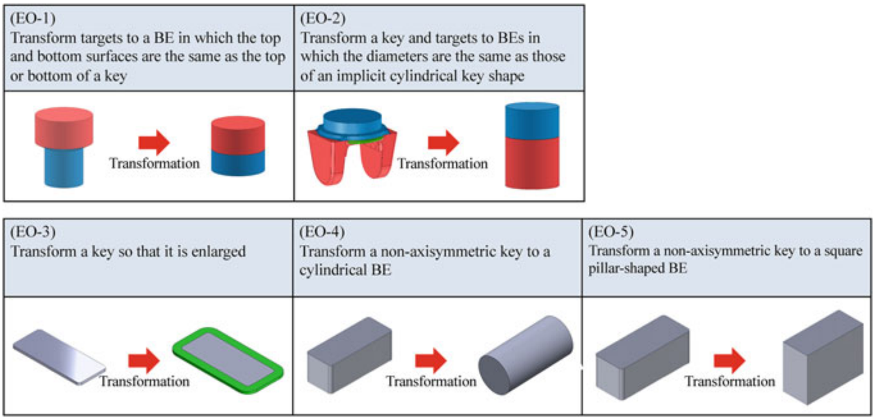


Fig. 5 Shape transformation rules for the outer shapes. (Color figure online)

Rule EO-1 for the outer shape adjusts the top and bottom surfaces of targets to the top or bottom surface of a key, which corresponds to forming via upsetting or forward or backward extrusion. Rule EO-2 adjusts the diameters of a key and targets to that of a cylindrical shape included implicitly in the key. EO-1 and EO-2 are similar to those defined for the GeneSteR method, whereas rules EO-3, EO-4, and EO-5 are new for the GeneSteR+E method. Rule EO-3 enlarges a key to a certain volume, which corresponds to cutting an edge off via blanking. Rule EO-4 restores to a cylindrical billet that is pressed in the direction perpendicular to its rotation axis, while rule EO-5 restores to a square billet.

Similarly, rule EI-1 for the inner shape is to adjust the top and bottom surfaces of targets to the top or bottom surfaces of a key, which corresponds to a forming via forward or backward extrusion. EI-1 and EI-2 are similar to those defined for the GeneSteR method, whereas, rules EI-4, EI-5, and EI-6 are new for the GeneSteR+E method. For example, rule EI-4 fills in a hole, which corresponds to cutting a hole via punching.

Rules O-1 and O-2 defined for the GeneSteR method are unified in rule EO-1 because the O-1 and O-2 geometric transformations are the same except for the surface shapes from an axisymmetric point of view. However, rule O-4 for design constraints regarding the limit of the forming load was eliminated because design constraints are considered in a later design phase as discussed in Sect. 4. A similar rule restructuring was also performed for the inner shapes.

4 Design Procedure for Forging Process Plans

Design constraints, such as the limit of the forming load, are not considered while transforming a shape according to the rules; therefore, some generated process plans may not be applicable to actual production. In addition, the forming steps in generated

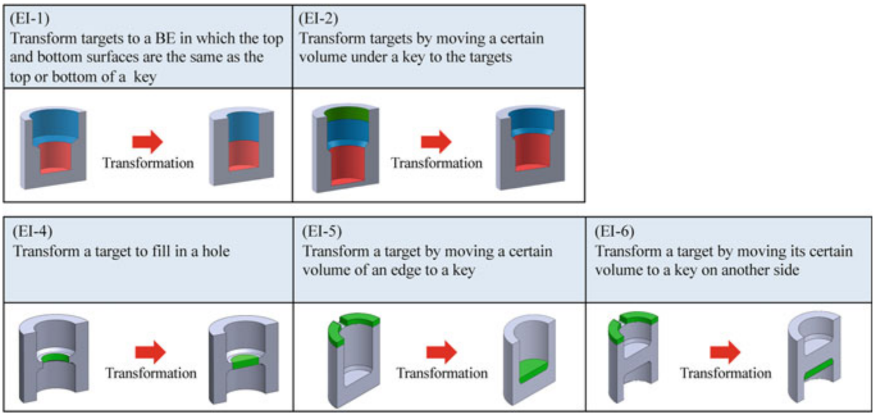


Fig. 6 Shape transformation rules for the inner shapes. (Color figure online)

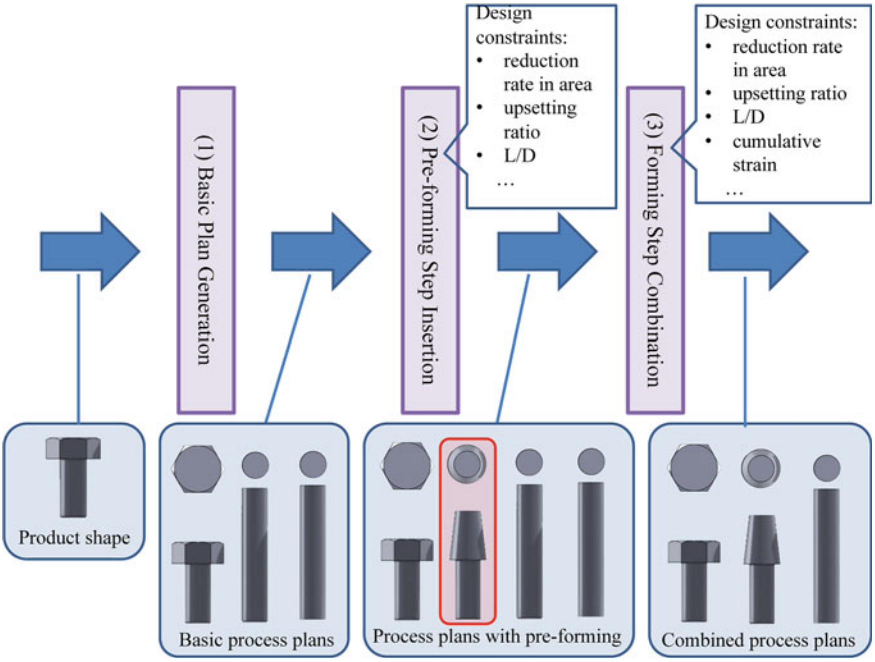


Fig. 7 Design procedure based on the GeneSteR+E method for forging process plans. (Color figure online)

plans may become too long to be practical because the rules are simple and the transformation is performed step by step. Therefore, the design procedure of the forging process is organized into three phases as shown in Fig. 7.

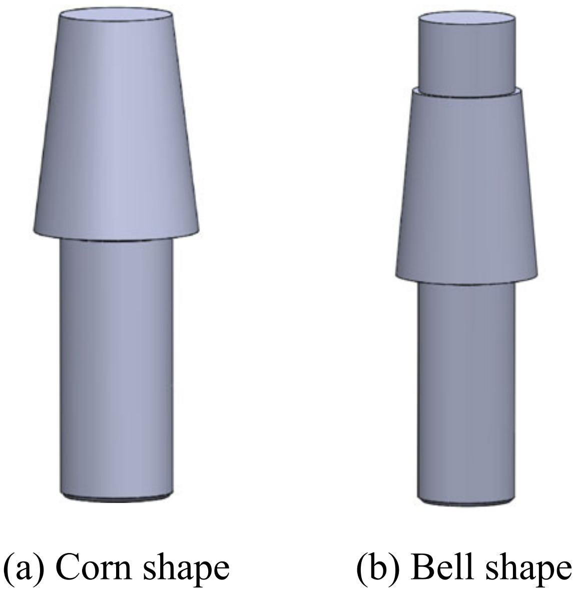


Fig. 8 Corn and bell shapes for preventing work material from being buckled by upsetting. (Color figure online)

First, basic process plans are generated by applying the GeneSteR+E method to a final forged product. The process plans generated in this phase may contain impractical forming steps because design constraints are ignored. Therefore, pre-forming steps are inserted into the plans in the second phase, considering design constraints, such as reduction rate in area, upsetting ratio, and L/D. Corn and bell shapes shown in Fig. 8 can be candidates for pre-forming steps inserted into process plans to prevent work material from being buckled via upsetting. Rule O-4 in the GeneSteR method was defined to prevent increases in the forming load by partly extruding work material forward and is realized in this phase as described in Sect. 3.2. Finally, multiple forming steps are combined into one by considering design constraints related to large shape changes in the third phase. The reduction in the number of forming steps will reduce production costs and lead time.

Because the shape transformation and the design constraints can be handled separately, unlike with the GeneSteR method, the management of the design knowledge becomes easier.

5 System Implementation and Experimental Results

The shape transformation rules are realized by using a set of basic shape operation functions that manipulate three-dimensional geometric models in SolidWorks through its OLE interface. New shape operation functions `CreateCuboid` and `ExpandByVolume` are added to the function set given in [9] for the new shape

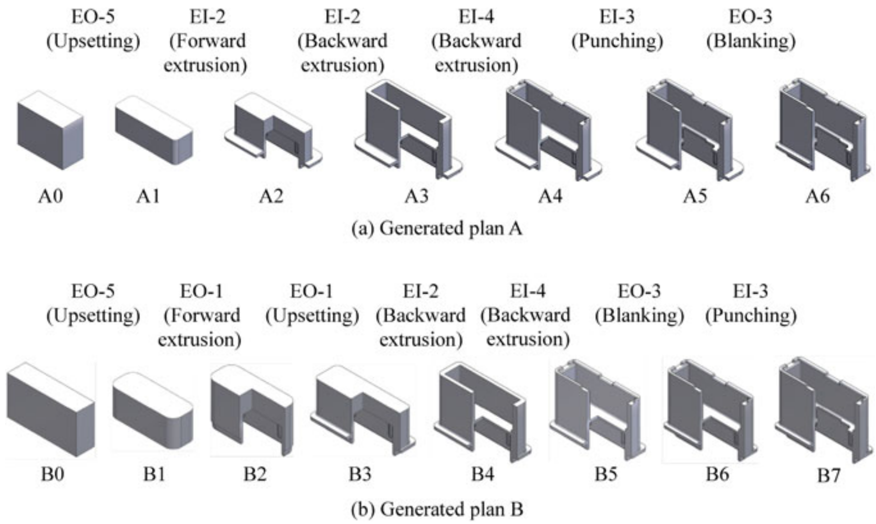


Fig. 9 Examples of generated process plans for an electrical connector. (Color figure online)

transformation rules. An experimental knowledge base, which implements the basic plan generation phase based on the GeneSteR+E method, is developed in the DSP knowledge representation language [10] using these functions.

The knowledge base was applied to cold- or warm-forged products, such as a hexagon-head bolt, a universal joint yoke, and an electrical connector. In the latter case, 162 process plans were generated in 6.55 h. Figure 9 shows two sample process plans generated via the knowledge base, while Fig. 10 shows one designed by an experienced engineer.

Plan A in Fig. 9 is similar to that of the engineer if it is modified by the next design phases described in Sect. 4. That is, the pre-forming step P2 is inserted between A2 and A3 for plastic deformability in the pre-forming step insertion phase, and the forming steps from A2 to P2 and from A3 to A4 are combined into single step to reduce the number of steps in the forming step combination phase. These results show that the GeneSteR+E method is applicable to forging process design, including blanking and punching, of totally non-axisymmetric products and can generate satisfactory process plans comparable to those by an experienced engineer. The execution time could be improved.

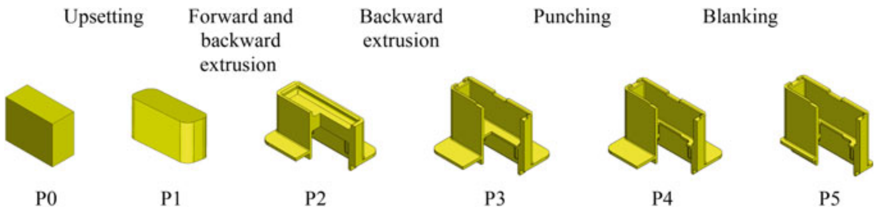


Fig. 10 Example of a process plan designed by an experienced engineer for an electrical connector. (Color figure online)

6 Conclusions and Future Work

This paper proposes a process planning method termed GeneSteR+E for totally non-axisymmetric cold- and warm-forged products that consist of only non-axisymmetric-shaped elements. It can generate plans for forging processes, including blanking and punching, for a forged product without relying on design cases.

An experimental knowledge base was implemented based on the GeneSteR+E method and applied to several forged products. The experimental results for an electrical connector had 162 generated process plans within 6.55 h. The generated plans included a plan comparable to one designed by an experienced engineer if the pre-forming step insertion and the forming step combination were applied to the comparable plan. These results show that GeneSteR+E is applicable to forging process design, including blanking and punching, of totally non-axisymmetric forged products.

The basic plan generation phase based on the GeneSteR+E method does not take care of design constraints; therefore, they have to be considered in the pre-forming step insertion and the forming step combination phases to produce deformable process plans. However, such design constraints have not been well systematized for non-axisymmetric forged products. Further research on this issue is essential to develop a practical knowledge base for forging process planning.

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