Determination of upset ingot dimensions during computer-aided forging design under fuzzy goals

S I Kanyukov, A V Konovalov and O Ju Muizemnek*

Institute of Engineering Science, Ural Branch of the Russian Academy of Sciences, Ekaterinburg, Russia

* olga@imach.utan.ru

Abstract. The paper describes an algorithm for determining reasonable dimensions of an upset ingot during computer-aided design of shaft press-forging under fuzzy goals. Fuzzy goals related to product metal elaboration quality and the complexity of its manufacture are formulated. Objective values of a design parameter for each goal are determined. Membership functions for possible solutions corresponding to these goals and the rule of choosing the most reasonable solution are constructed. Two examples of solving the problem depending on the selected goals are given. The proposed algorithm allows one to choose the most reasonable solution from a set of feasible ones and reduces human participation in the computer-aided design process. The developed approach can be applied to solving other problems of press forging, such as choosing an ingot, determining the necessity of the billet upset operation, determining the cogged billet dimensions, etc.

The computer-aided design of press-forging technology is a rather complicated process owing to the poorly formalized subject area. As a result, different technologies can offer different solutions for the same forged part depending on stated goals, even within the same enterprise. Such goals include, for example, reasonable metal saving, low labour consumption for forged part production, etc. In this case, the words “reasonable”, "low”, understandable to man, are fuzzy in terms of algorithms and programs, and they require special methods for their formalization. Therefore, the computer-aided design of a technological process is performed under conditions of fuzzy goals and limitations.

Due to the lack of subject area formalization, developers of computer-aided process planning (CAPP) systems, on the one hand, have to pay much attention to the interactive communication of users with the system [1-3]. On the other hand, the natural desire of the developers is to reduce the share of human participation in the computer-aided design process. Therefore, while creating CAPP systems, much attention has always been paid to improving their intellectual level by using various methods of artificial intelligence [4, 5]. The theory of decision making under fuzzy conditions, according to the Bellman-Zadeh scheme [6], is promising for these purposes.

Fuzzy logic is used to solve a variety of problems arising during a design process. The study [7] described how the fuzzy modelling theory helps to resolve contradictions within a design process. The advantage of the fuzzy approach to computer-aided design of a forged part was demonstrated in [8]. Expert computer systems of technology design based on fuzzy logic, including those for cold stamping, were described in [9, 10]. Those studies emphasized that design uncertainty is associated
with the subjectivity of decision making and that it is advisable to use fuzzy logic to obtain final decisions.

In general, the technological process of press forging includes the following main stages.

**Ingot selection.** A minimum-weight ingot is selected. This allows one to produce a required forged part taking into account inevitable technological losses of metal.

**Preforging.** Preforging includes rounding of the cast ingot (the resulting product is termed a billet), billet upsetting (upset billet) and cogging into a blank with a circular cross section.

**Final forging.** Sequential forming of the circular blank into the final forged part.

Figure 1 exemplifies a fragment of a process sheet for shaft forging.

The multiplicity of a forging design problem solution implies that the value of each process parameter $Y$ should belong to its technological interval $[Y_{\min}, Y_{\max}]$. The boundaries of this interval are determined by the general rules of forging technology design [11] and technological instructions of enterprises. For example, many possible versions of the upset billet correspond to each solution of the problem of determining billet dimensions (see figure 1). Moreover, the dimensions of all the subsequent intermediate blanks, and hence the number of blank preheatings during the forging process, the choice of tools, the actions of the forging team, are dependent on the upset billet dimensions.

![Figure 1. A fragment of a process sheet for shaft forging](image)
Thus, it is necessary to be guided by certain principles of rationality in terms of the total design process problem for the determination of a specific value of $Y \in [Y_{\min}, Y_{\max}]$. At the same time, the selection of reasonable values for the process parameters from the intervals of their feasible values depends on the stated goals.

A concept of choosing a reasonable decision during computer-aided design of press forging under conditions of uncertainty and numerous pursued goals was described in [12]. This concept is based on the theory of decision making according to the Bellman-Zadeh scheme [6]. In this paper, the concept is concretized for solving the problem of the determination of reasonable upset billet dimensions during preforging (see figure 1).

While forging on presses, the main indicator of metal elaboration quality is the amount of strain in the final forged part, which is generally evaluated by the expression $\left( \frac{D}{D_p} \right)^2$, where $D$ is the diameter of the upset billet and $D_p$ is the overall diameter of the final forged part. Two process parameters govern the process of billet upsetting: the amount of strain during upsetting and the manufacturability of the process. The amount of strain is determined by the ratio $\frac{L_s}{H}$, where $L_s$ is billet length and $H$ is upset billet height. The manufacturability of upsetting is evaluated by the ratio $\frac{H}{D}$. In our example, $D = 1020$ mm, $D_p = 560$ mm, $L_s = 1800$ mm, and $H = 705$ mm.

The analysis of the existing generally accepted recommendations, enterprise instructions, and forging process sheets allow one to formalize requirements imposed on the upset billet dimensions and to write them in the form of the inequality system

$$\left( \frac{D}{D_p} \right)^2 \geq 3, \quad \frac{L_s}{H} \geq 2, \quad \frac{H}{D} \geq 0.6. \quad (1)$$

It should be noticed that, although the first restriction in the system of inequalities (1) corresponds to the generally accepted recommendations, the analysis of forging process sheets for real shafts, especially for critical forgings, shows that forging technology developers generally tend to set the amount of strain in a final forged part with some reserve, for example, $\left( \frac{D}{D_p} \right)^2 \geq 4$. They consider that, under this condition, the product metal will be elaborated with guaranteed quality.

It is easy to see that the desire to increase the amount of strain in the upset billet, as well as in the final forged part, i.e. the desire to increase the value of $D$, is limited by the third inequality in system (1). This condition is interpreted as follows. An increase in $D$ improves the quality of metal elaboration, but it degrades the manufacturability of ingot upsetting and increases the complexity of subsequent ingot processing, since a larger volume of metal will have to be moved during subsequent forging operations. The latter may lead to microcracking in the metal.

The problem of determining reasonable upset billet dimensions is solved in steps.

**Step 1.** The choice of the process parameter $Y$ and the determination of technological restrictions imposed on the values $Y_{\min}$, $Y_{\max}$ of this parameter.

Since the diameter $D$ and the height $H$ of the upset billet are related to each other through the volume constancy condition, the diameter $D$ can be taken as the parameter $Y$. The value $Y_{\min} = D_{\min}$ is determined from the first two inequalities involved in system (1), whereas the value $Y_{\max} = D_{\max}$ is determined from the third inequality in system (1). For our example, we have $Y_{\min} = 970$ mm, $Y_{\max} = 1070$ mm. Here and below, the dimensions are rounded off to 5 mm.
Step 2. The choice of the pursued goals \( C_i, i = 1, 2, \ldots, n \) (\( n \) is the number of goals) for the design of the upset billet and the determination of the value of its diameter \( Y_i^C = D_i^C \) for each goal. When the upset billet diameter reaches this value, the corresponding \( i \)-th goal is fully achieved.

Let us define three design goals \( C_1, C_2, \) and \( C_3 \) (\( n = 3 \)).

Goal \( C_1 \). The complexity of subsequent forging of an upset billet should be as minimal as possible. The smaller the upset billet diameter, the smaller the metal volume should be moved during subsequent forging, hence \( Y_1^C = D_1^C = D_{\text{min}} = 970 \) mm.

Goal \( C_2 \). The quality of metal elaboration in an upset billet should be as high as possible. It follows from the third inequality in system (1) that \( Y_2^C = D_2^C = D_{\text{max}} = 1070 \) mm.

Goal \( C_3 \). The quality of metal elaboration in a final forged part should be guaranteed to be high. It follows from the inequality \( \left( \frac{D}{D_p} \right)^2 \geq 4 \) that \( Y_3^C = D_3^C \geq 2 \times D_p = 1120 \) mm.

Step 3. The determination of the membership functions \( \mu_1, \mu_2, \mu_3 \) for the upset billet diameter \( D \) corresponding, respectively, to the stated goals \( C_1, C_2, \) and \( C_3 \).

The concept of membership functions was introduced in the theory of fuzzy sets [6]. For a fuzzy set, unlike classical sets, each element can belong to a set only partially. The degree of the element membership in a fuzzy set is characterized by the membership function, the values of which lie within the interval \([0, 1]\). When this value is equal to 1, it means that the element fully belongs to the set. When it is equal to 0, it means that the element is absent from the set.

According to [12], the membership function \( \mu_i \) of the parameter \( Y \) corresponding to the stated goal is taken as

\[
\mu_i = \frac{1}{1 + \left( \frac{Y - Y_i^C}{Y_{\text{max}} - Y_{\text{min}}} \right)^2}, \quad i = 1, 2, 3.
\]  

(2)

After substitution of the values \( Y_{\text{min}}, Y_{\text{max}}, \) and \( Y_i^C \) obtained in steps 1 and 2 into (2), we arrive at three membership functions,

\[
\mu_1 = \frac{1}{1 + \left( \frac{D - 970}{100} \right)^2}, \quad \mu_2 = \frac{1}{1 + \left( \frac{D - 1070}{100} \right)^2}, \quad \mu_3 = \frac{1}{1 + \left( \frac{D - 1120}{100} \right)^2}.
\]  

(3)

Step 4. The determination of the resulting membership function \( \mu \) of the upset billet diameter \( D \) corresponding to all the three goals simultaneously.

The resulting membership function \( \mu \) taking into account the domain of definition \( D \in [D_{\text{min}} = 970, D_{\text{max}} = 1070] \) is taken in the form

\[
\mu = \begin{cases} 
0, & \text{if } D < 970 \lor D > 1070 \\
\min(\mu_1^{\alpha_1}, \mu_2^{\alpha_2}, \mu_3^{\alpha_3}) & \text{if } 970 \leq D \leq 1070 
\end{cases}
\]  

(4)

where \( \mu \in [0, 1] \), \( \alpha_1, \alpha_2, \alpha_3 \) are the exponents characterizing the relative importance of the stated goals \( C_1, C_2, C_3 \), respectively. Herewith, \( \alpha_1, \alpha_2, \alpha_3 \geq 0, \sum_{i=1}^{3} \alpha_i = 1 \).

Thus, the resulting membership function takes into account the relative importance of all the three goals. The closer the value of the function \( \mu \) to 1, the better the problem solution corresponds to all the goals simultaneously. The solution of the problem is to find the value \( D \in [970, 1070] \) corresponding to the maximum value of \( \mu \) in (4).
The solution of the problem for the goals of equal importance is graphically shown in Figure 2.

![Figure 2](image-url)

**Figure 2.** The functions \( \mu_1^{\alpha_1}, \mu_2^{\alpha_2}, \mu_3^{\alpha_3}, \) and \( \mu \) for equally important goals

Thin solid lines in figure 2 show graphs of the functions \( \mu_1^{1/3}, \mu_2^{1/3}, \mu_3^{1/3} \) calculated in accordance with equation (3). The graph of the function \( \mu \) in equation (4) is represented by a bold line bordering the shaded area. As shown in figure 2, the maximum value of \( \mu \) corresponds to the value \( D \approx 1045 \) mm, which, in this case, should be considered the most reasonable solution to the problem.

The result of solving the problem with goals of unequal importance, for example, \( \alpha_1 = 0.5, \alpha_2 = 0.4, \alpha_3 = 0.1 \), when the goal \( C_2 \) is 4 times as important as the goal \( C_1 \), and the goal \( C_1 \) is 5 times as important as the goal \( C_3 \), is shown in figure 3. For unequally important goals, the desired value of the upset billet diameter changes to become equal to 1017 mm.

![Figure 3](image-url)

**Figure 3.** The functions \( \mu_1^{\alpha_1}, \mu_2^{\alpha_2}, \mu_3^{\alpha_3}, \) and \( \mu \) for unequally important goals

**Conclusion**

The algorithm for solving the problem of determining the reasonable upset billet diameter during computer-aided design of shaft press forging in terms of fuzzy goals has been proposed. Fuzzy goals have been related to the quality of product metal elaboration and the complexity of forging production. The objective values of the design parameter for each goal have been determined. Membership functions for possible solutions corresponding to these goals and the rule of choosing the most reasonable solution have been constructed. Two examples of solving the problem depending on the selected goals have been demonstrated. The proposed algorithm allows one to choose the most reasonable solution from a set of feasible ones and reduces human participation in the computer-aided design process. The developed approach can be applied to solving other problems of press forging,
such as choosing an ingot, determining the necessity of billet upsetting, determining the cogged billet dimensions, etc.

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