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Citation: *AIP Conf. Proc.* **1353**, 419 (2011); doi: 10.1063/1.3589551

View online: <http://dx.doi.org/10.1063/1.3589551>

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INVESTIGATION OF THE INFLUENCE OF TOOL GEOMETRY ON EFFECTIVE STRAIN DISTRIBUTION IN FULL FORWARD EXTRUSION

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Abstract. Due to strain hardening of the material, the hardness of cold forged parts is considerably improved. It is well known that the hardness of cold forged parts is closely related to its deformation, and that this relation is not dependent on the deformation process. The effective strain defines the local deformation, and can be determined in simulation of the cold forming process. In order to reach the required or to set specific hardness distribution with cold forging without any heat treatment processes, it is necessary to find out which manufacturing parameters influence the effective strain, and determine the effects of these parameters. The research work covered in this paper investigates the influence of the die geometry (as manufacturing parameter) on the effective strain. For that, a full forward extrusion process was modeled using the FE-software Simufact.Forming and three parameters of the die geometry, namely the deformation ratio, the shoulder radius and the opening angle were varied. The maximum effective strain from each combination is determined, and the effects of each considered parameter as well as the effects of interactions between these factors are checked.

Keywords: effective strain, deformation ratio, full forward extrusion, Finite Elements Method, Design of Experiments.

PACS: 81.20.Hy

INTRODUCTION

During cold forging processes the hardness of the components is considerably improved due to strain hardening of the material. Hardness as a measure of material's resistance to wear and permanent deformation is an important quality parameter for cold forged parts. Through estimating the hardness distribution, it is possible before manufacturing the components to predict whether the end product will have the desired hardness levels or require a final heat treatment [1]. The estimation of the hardness distribution can also facilitate the decision to complete the process in one or many stages with intermediary heat treatments. Knowing that hardness increases with increased amount of deformation, many studies showed in the past that hardness in a cold forged part is strongly related to effective strain [2-6]. It is also mentioned that this relation is not dependent on the deformation process [7]. That means, the same relation is expected both in a forward extrusion as in a backward extrusion. In this way, it is possible to predict the hardness distribution in cold forged parts if the relation between the hardness and the effective strain of the material and the effective strain distribution in the manufactured part are known [8].

Nowadays, the design of cold forging processes takes place primarily through the application of numerical process simulation using the finite element method. It is possible to determine the characteristic component properties such as the effective strain distribution of the components with high local resolution [9]. Knowing the relation between the hardness and the effective strain of the material, it is possible to reach the required or to set specific components' hardness distribution during the process simulation without any heat or post treatment processes. In order to optimize the hardness distribution in cold forged parts, it is crucial to find out how the effective strain can be influenced. In this paper the tool geometry was selected as influencing factor on the effective strain. It is well known that, in extrusion, geometric parameters like the extrusion ratio, which is defined as the cross-sectional area of the billet divided by the cross-sectional area of the extruded part, have a considerable impact on the punch force [10]. The punch force itself affects the yield strain and thus the strain distribution. To enable the investigation of this influence, a full forward extrusion process was modeled using the FE-software Simufact.Forming. Within a 2^k -full factorial experimental design, the tool geometry was varied, and for each geometry variation the maximum effective strain in the extruded part was locally determined. Afterwards, the effects of the tool geometry parameters and the interactions between them were determined.

PROCESS SIMULATION

Variation of the Die Geometry

Figure 1 shows the die geometry for full forward extrusion. During the extrusion process plastic deformations occur mainly in the die shoulder, which is the transition area between both die diameters. For this reason, only the geometrical parameters of this area were selected, namely the diameters d_0 and d , the shoulder radius r and the opening angle 2α .

FIGURE 1. Die geometry with conical form.

According to Eq. 1, both die diameters were substituted through the deformation ratio φ . The deformation ratio is a global dimension for extrusion processes, and is defined as a relation between the cross-sectional area of the billet A_0 and the cross-sectional area of the extruded component A . The deformation ratio φ must be distinguished from the effective strain φ_v , which characterizes the local deformation in the part. In order to avoid tool failure, it is recommended for full forward extrusion processes not to exceed a value of 1.6 for the deformation ratio [10].

$$\varphi = \ln\left(\frac{A_0}{A}\right) = 2 \cdot \ln\left(\frac{d_0}{d}\right). \quad (1)$$

Together with the deformation ratio the opening angle influences the process force. Due to the deviation of the material flow in the die shoulder, the maximum process force grows usually with an increasing opening angle [10]. Knowing that the process force depends on the workpiece deformation, the deformation ratio as well as the opening angle have been selected for the geometry variation. Prior to this paper, many experiments were carried out to find out the influence of the shoulder radius on the process force. For that, the deformation ratio and the opening angle were kept constant at 1.4 and 90° respectively. These experiments showed that the maximum process force increases by 7% by reducing the shoulder radius from 1 mm to 0.5 mm (see Figure 2). Hence, the shoulder radius had to be selected for the geometry variation.

FIGURE 2. Influence of the shoulder radius on the punch force.

Constitution of the Simulation Model

Figure 3 shows the simulation model with the contact bodies, namely the billet, the die, two reinforcement rings and the punch. The billet is enclosed by the die, and the temperature of the two contact bodies is 20° C. The punch is moving to the billet with a speed of 10 mm/s. The extruded material is flowing into the die. The interference fit assembly has a conical joint with an angle of inclination of 1°. In order to avoid plastic deformations in the die, two reinforcement rings are required. To avoid cold-welding in the interference fit assembly, the high speed steel 1.3343 has been selected for the die, and the hot work tool steel 1.2343 for the reinforcement rings. The billet is the only plastic deformable body, and for the simulation the annealed steel 1.0501 (C35) has been selected. The friction factor m between the billet and the die was set at 0.04, which is standard for full forward extrusion [10]. In order to reduce the computing effort needed for this investigation, a 2D-axialsymmetric FE analysis has been preferred.

FIGURE 3. Simulation Model.

The initial FE mesh of the billet includes 400 elements. During the simulation of cold forging processes the initial FE mesh becomes progressively distorted because of plastic deformation. An excessive element distortion could avoid the solution convergence, and stop the simulation. In order to surmount this problem, an adaptive remeshing function is included in Simufact.Forming. To avoid any element distortion in the shoulder die and particularly near the shoulder radius, the adaptive remeshing criterion advancing front quad has been selected. In contrast to the overlay remeshing, where all elements have the same length, this remeshing method varies the element length automatically, and refines the mesh where high element distortions occur. For the simulation model the element length varies between 0.05 and 0.3 mm, and more than 2000 elements were used for the billet.

RESULTS AND DISCUSSION

In order to enable the identification of effects and the occurring interactions between the parameters of the die geometry, 8 parameter combinations have been investigated. The analysis of the maximum effective strain for every single parameter combination allows the calculation of every effect and parameter interaction, according to the 2³-full factorial process layout using the design of experiments (DoE). The limits of the three selected parameters are listed in Table 1.

TABLE 1. Parameter limits.

Parameter		Lower limit	Upper limit
Deformation ratio	φ	0.36	1.38
Opening angle	2α	60°	90°
Shoulder radius	r	0.5 mm	1 mm

The maximum effective strains resulting from the variation of the die geometry are displayed in Figure 4. The left points correspond to $\varphi = 0.36$, and the right points correspond to $\varphi = 1.38$. Points resulting from the angle 90°

are connected with dashed lines, and the others points correspond to the angle 60° . The connection lines indicate the trend due to the variation of the deformation ratio, and do not represent any relation between the deformation ratio and the maximum effective strain. The red color is attributed to the radius 0.5 mm, and the blue color to the radius 1 mm. The first impression from the figure 4 is that the maximum effective strain is considerably increasing with the deformation ratio. As expected from Eq. 1, the smaller the die inner diameter d is, the higher is the component deformation and thus the maximum effective strain. Considering the parameter combination $2\alpha = 60^\circ$ and $r = 0.5$ mm, the increase of the deformation ratio from 0.36 to 1.38 yields a maximum effective strain raise of about 1.1. As expected, due to the material flow deviation, the values at the angle 60° are generally smaller than at the angle 90° . However, the influence of the angle decreases with increasing deformation ratios. Considering for example the radius 0.5 mm, the difference between the maximum effective strain of both angles decreases from 0.43 at $\varphi = 0.36$ to 0.06 at $\varphi = 1.38$. For each combination of deformation ratio and opening angle the maximum effective strain at the radius 0.5 mm is generally higher than at the radius 1 mm. Only at $\varphi = 0.36$ and $2\alpha = 60^\circ$ is no difference detectable between both radii. The results on figure 4 show that the effective strain distribution can be set through variation of the die geometry.

FIGURE 4. Maximum effective strains resulting from each parameter combination.

FIGURE 5. Pictures of the simulation. **a.** Variation of the deformation ratio at $2\alpha = 60^\circ$, $r = 1$ mm: $\varphi = 0.36$ (left) and $\varphi = 1.38$ (right). **b.** Variation of the radius at $2\alpha = 90^\circ$, $\varphi = 0.36$: $r = 0.5$ mm (left) and $r = 1$ mm (right). **c.** Variation of the angle at $\varphi = 1.38$, $r = 1$ mm: $2\alpha = 90^\circ$ (left) and $2\alpha = 60^\circ$ (right).

Figure 5 shows the pictures resulting from the simulation of the different processes. The influence of each parameter on the effective strain distribution is separately considered. Figure 5.a represents the variation of the deformation ratio at $2\alpha = 60^\circ$ and $r = 1$ mm. The effective strains at $\varphi = 1.38$ are higher than at $\varphi = 0.36$. Thus, it is

confirmed again that the effective strain increases with the deformation ratio. The shoulder radius at $\varphi = 0.36$ and $2\alpha = 90^\circ$ is considered on figure 5.b. The decrease of the radius from 1 mm to 0.5 mm yields an effective strain raise of 0.1 near the radius. Furthermore, the strain distribution is less homogeneous at the radius 0.5 mm than at the radius 1 mm. Figure 5.c shows different strain distributions between both angles at $\varphi = 1.38$ and $r = 1$ mm. The effective strain distribution extends over 5 graduations at 90° from 1.40 to 1.90. However, only 3 graduations are displayed at 60° . Thus, the strain distribution becomes less homogeneous with increasing opening angles.

It can be stated from figures 4 and 5 that die geometry combinations with high deformation ratios, large opening angles and small shoulder radii are recommended to reach high effective strains in cold forged parts. Concerning the variation of the radius, the increase of the strain was observed near the radius, at the exit of the die shoulder, and cannot be transmitted to the rest of the part. In addition of that, the strain distribution becomes less homogeneous through increasing the opening angle.

TABLE 2. Effects of the die geometry variation on the maximum effective strain.

Nr.	φ	w	r	φ^*w	φ^*r	w^*r	φ^*w^*r	y_i
1	+	-	-	-	-	+	+	1.84
2	-	-	-	+	+	+	-	0.76
3	+	+	-	+	-	-	-	1.89
4	-	+	-	-	+	-	+	1.01
5	+	-	+	-	+	-	-	1.69
6	-	-	+	+	-	-	+	0.75
7	+	+	+	+	+	+	+	1.83
8	-	+	+	-	-	+	-	0.95
Sum	3.78	0.64	-0.28	-0.26	-0.14	0.04	0.14	
Effect	0.94	0.16	-0.07	-0.06	-0.03	0.01	0.03	

The influence of the die geometry on the maximum effective strain and on the strain distribution has already been established. Now, it is necessary to quantify the effects of the three parameters and the interactions between them. These effects are shown in Table 2, calculated on basis of the DoE formalism [11]. An effect is per definition the difference of the response, in this case the change of the maximum effective strain, when changing the particular parameter from the low setting to the high setting (see Table 1). A negative change indicates that the parameter shift from the low to the high setting will result in a decreasing maximum effective strain. For the calculation of the effects each parameter is divided in two categories: the lower parameter limit takes the factor (-), and the upper parameter limit takes the factor (+). For each geometry combination the maximum effective strain y_i is multiplied by the factor of the considered parameter limit. To determine the effect of the parameter, all the multiplied values are summed and averaged. The interactions are also determined on the same way. To find the factor of the interaction, the factors of each combined parameter are multiplied together.

FIGURE 6. Effects and parameter interactions.

Figure 6 displays the results of the analysis of the effects of the geometric parameters and the interactions between them. The largest impact on the maximum effective strain is caused by the deformation ratio φ and the opening angle. However, the effect of the deformation ratio, which is relatively dominant, is 5 times larger than the effect of the opening angle and even 13 times as the effect of the radius. The parameter interactions are rather weak (-0.03 for the interaction between φ and r) or not remarkable (0.01 for the interaction between 2α and r). Due to the discretisation of the model, some numerical errors may occur during the FE-simulation but the repeatability of the estimation of the strain using the same remeshing function is ensured. It is not possible to make a statement about the significance level of the determined effects and interactions because the results do not have any statistical spread. This analysis allows weighting the different parameters and thus to classify the parameters according to their importance.

CONCLUSION

The results from the investigation show clearly that in full forward extrusion high deformation ratios combined with large angles and small radii tend to high effective strains in the part. Without statistical spread of the results it is not possible to make a statement about the significance of the parameters. Thus, this study only weights the parameters. The deformation ratio has the largest effect among the three parameters. Due to the deviation of the flow lines at the beginning as well as at the end of the die shoulder, large opening angles and small radii tend to increase the process force. The research work covered in this paper shows also that at small radii and large angles the strain distribution becomes less homogeneous: the effective strain increases near the shoulder radius and the strain distribution extends over more graduation levels. Hence, the process should be designed accordingly, depending on which quality criterion is required for the part: either more effective strain and thus more hardness, or more homogeneity of the strain distribution. This study shows that it is possible to set the effective strain with changing the die geometry. In order to manufacture load-adjusted components, the next step would be to determine the influence of the effective strain on the component's strength.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support of the Federal Ministry for Education and Research (BMBF), which supported the research project "Load oriented component properties for lightweight and high performance applications through efficient, optimized cold forming processes" (KAMASS).

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