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Influence of die geometry on performance in gradation extrusion using numerical simulation and analytical calculation

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ABSTRACT

Forming by gradation extrusion enables severe plastic deformation with a large gradient of plastic strain resulting in a correlating gradient of the microstructure. Materials with tailored properties can thus be provided. Controlling the gradation of the microstructure also requires knowledge of the interaction of forming process and a special die geometry. Based on an analytical calculation approach, different geometry variants are characterized. Additionally, selected geometrical variants are studied more comprehensively by numerical simulation. The mechanisms of the interaction and possibilities of influencing the deformation process by die design and process parameter optimization are presented and analyzed.

1. Introduction

The gradation extrusion (GE) forming process has been developed to provide materials with tailored properties by adapted severe plastic deformation (SPD). The processing leads to a gradient of the deformation and microstructure. The excellent properties of severely deformed materials can be achieved without processing the complete material volume. A combination of a ductile core section with high strength, ultrafine-grained lateral section in a component can be realized. Preliminary studies showed that this principle can be successfully applied to process aluminium materials [1–3].

The key feature of the process is the generation of a gradient of deformation by using so called SPD-forming elements. These elements are integrated into the die to create local additional deformation, which is intended to produce a specific property modification with required microstructural and mechanical characteristics. The angled forming elements are designed with the goal to create deformation conditions similar to ECAP (Equal Channel Angular Pressing) processes. In contrast to ECAP, these conditions are not created throughout the complete material volume, but only locally in the lateral area of the component. Thus, the forming process can be described as a combination of repetitive extrusion deformation and an ECAP-like deformation on the lateral area of the workpiece [4]. The ECAP-like deformation is similar to a route C in an ECAP process [5].

In general, the size and distribution of property modifications generated by GE depends on the design of the SPD-forming elements. A large range of design choices exists regarding geometry, number, distribution, etc. of elements. The interaction of these geometrical features as well as their interaction with processing conditions are yet not fully understood and have not yet been investigated comprehensively. The present work provides a contribution to understand these core features of GE.

The general die design for the GE process can be described by two basic variants shown in Fig. 1. Design A consists of two die sections, one with angled forming elements and one section for the final diameter reduction. This die variant was the first approach in the development of the GE process and has been used to demonstrate its potential [1,2].

Design B combines the angled SPD-forming element geometry with a stepwise diameter reduction without any diameter enlargement during forming. This die design is free of undercuts. However, the entrance conditions and the stepwise process differ from die design A and from the standard impact extrusion.

The deformation characteristics of the two design approaches are investigated using a calculation method and FE process

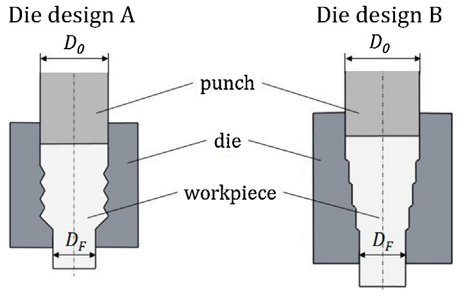

Fig. 1. Design variants of GE-die geometries.

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simulation. The reduction, expansion and shearing produced during processing result in a combined effect on the effective strain, which is a suitable indicator of severe plastic deformation.

2. Geometrical features of the die designs

The geometrical characterization of the extrusion dies shown in Fig. 2 specifies the most relevant design parameters of the die. Both die variants are defined by the same initial diameter D_0 and final diameter D_F. The two variants exhibit an angled geometry in the forming element section shown in Fig. 2. The SPD-forming elements are symmetrically designed, the angles ϕ are identical and continuously repeated.

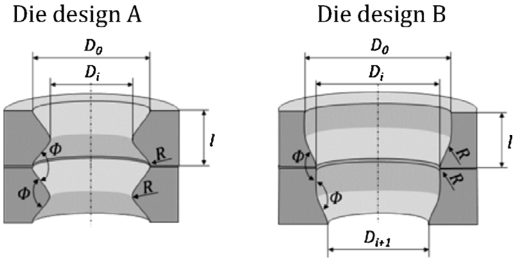

Fig. 2. Forming element geometries for the two die designs.

In design A the initial and final angle are different due to geometry transition. Besides the initial diameter D_0 and the final diameter D_F, the radii R and the number of stacking forming elements are parameters that affect the material flow. In design B the final diameter in the first forming element D_i corresponds to the initial diameter of the next element. As there is no increase of the diameter during forming, the forming elements have to be adapted in every step. The basic geometry of each step remains the same while the diameters stepwise decrease.

Table 1 gives an overview of the main geometrical parameters for the two die variants. For both designs 4 forming steps are used in the calculation.

The investigations focus on the influence of the size of angle ϕ and forming element length l. The initial and final diameters are kept constant. The radii R have a significant influence on the forming process. However, in order to reduce complexity and allow for a comparison of the two die designs, the radii are set at an equal and constant value. Basically, at smaller radii the deformation increases and material flow is more restricted resulting in a higher tendency towards material and process failure.

Table 1
Investigated geometrical values of the two die design variants.

		Design A	Design B
Initial diameter	D_0	16 mm	
Final diameter	D_F	10 mm	
Inner diameter	D_i	$D_i = f(\phi, R)$	Diameter-reduction in 1.5 mm steps
Radius	R	0.2 mm	
SPD-forming element angle	ϕ	90°; 105°; 120°; 135°; 150°; 165°	
SPD-forming element length	L	4; 4.5; 5; 6; 6.5; 8; 10; 12 mm	

3. Methods for characterization of the material deformation

In order to characterize and compare the deformation behaviour of the material during the process of gradation extrusion, the numerical simulation is supplemented by an analytical calculation. Using the analytical approach, the influence of only geometrical die features can be analyzed without taking into account the specific material behaviour and friction.

The major advantage of an analytical approach is to provide a general evaluation of die geometry fast and easily. The design of the analytical model requires taking the specifics of the GE process into account, which exhibits combined characteristics of an extrusion and an ECAP process. For these conditions an analytical approach was developed and applied here [4]. The calculation is based on geometrical factors only.

As a second method for characterizing the deformation behaviour of the material during GE, a numerical simulation has been carried out. The simulation takes aspects of the forming process into account, which are not regarded in the analytical calculation model. The material behaviour, respectively the hardening effect, leads to a non-homogeneous flow resistance. The material flow affects the strain generation in the GE process and the gradient of the strain generation is characterized. Furthermore, friction influences the forming process at the contact between workpiece and die considerably.

3.1. Analytical calculation approach

The approach for the calculation of the total effective strain φ_v in the lateral area during GE is based on separating the process into two distinct deformation mechanisms: the extrusion process and the ECAP-like deformation [4]. Both mechanisms consist of several steps with effective strains of φ_{i_IE} for each extrusion step and φ_{j_ECAP} for the ECAP-like deformation steps. When using die design A, the diameter of the workpiece is alternatingly reduced and expanded whereas using die design B, it is reduced stepwise. The reduction, respectively expansion, is calculated by Eq. (1). Every impact extrusion step i contributes to the overall strain generation:

$$\varphi_i\_IE = \ln(1 + \epsilon_A) \quad (1)$$

For the ECAP-like deformation in the near-surface area an ECAP channel of a specific width is assumed with several sequential ECAP-steps (Fig. 3). One side of the channel corresponds to the die geometry. A symmetrical channel is assumed with width b, angle ϕ and radii R. Every single die angle is recognized as an ECAP-angle. As a result of the 4 forming steps, both die designs include 8 ECAP-like deformation steps. The size of the entry and exit forming angles of die design A are different from the regular value of all other steps due to the transition of geometry.

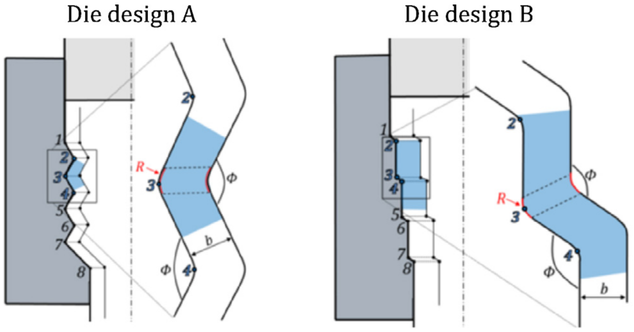

Fig. 3. ECAP-like deformation in the lateral area for die design A and B.

Using the equation by Segal [6], the effective strain for each ECAP-like deformation j can be calculated as follows:

$$\varphi_j\_vECAP = \frac{2}{3}\cdot\cot\left(\frac{\phi}{2}\right) \quad (2)$$

The total effective strain is calculated by summing up the values for i extrusion steps and j ECAP forming steps, whereas for die design A $i = 1\ldots8$ and $j = 1\ldots8$ and for die design B $i = 1\ldots4$ and $j = 1\ldots8$, respectively.

$$\varphi_v = \sum_{i=1}^{n}|\varphi_i - vIE| + \sum_{j=1}^{m}|\varphi_j - vECAP| \quad (3)$$

The total effective strain φ_v represents the strain within a channel near the forming elements, respectively the severely

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