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NUMERICAL MODELLING OF CONSTRAINED GROOVE PRESSING WITH DEFORM 3D SOFTWARE

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Abstract

The Constrained Groove Pressing (CGP) is one of the many forming processes, which are used for preparation of ultrafine-grained structure in materials. With this technique, it is possible to manufacture bulk fine-grained products using a wide range of steels and alloys. The finite element method (FEM) modelling may be used for verification of design tool parameters, for optimization of the shape of the CGP-tools and for optimization of the forming process. It provides significant information on the effects of the tool geometry, material properties and friction upon the flow of material. In this study, numerical modelling has been used for investigation of forming with dies of different groove shapes, varying sample thickness and two different specimen materials (steel and aluminium alloy). The distribution and amount of effective strain and the magnitudes and changes in forming forces were evaluated. The calculation has shown the differences between the alternative forming configurations in terms of the distribution and amount of effective strain. The computation results were used as a basis for design of optimum-shaped tools and verifying the technological process. This optimum alternative has been experimentally tested. The plates prior to CGP had a coarse-grained recrystallized structure with large scatter in grain size. Specimens were forged with up to four strokes, each stroke introducing the strain of about 0.7 in the deformed segments. The impact of the experimental forming upon microstructure development was investigated with light microscopy, scanning electron and transmission electron microscopy of thin foils. The results show that the Constrained Groove Pressing with one completed pass resulted in formation of non-uniform finer microstructures with some new grains formed by intensive deformation and dynamic recrystallization process. The presence of low tensile and compressive strain in flat segments of specimens, resulted as well in grain refining process, as suggested by numerical simulation, has been confirmed by transmission electron microscopy observation. However, higher number of passes is required to further homogenize and refine the microstructure.

Key words: Constrained Groove Pressing (CGP), numerical simulation, transmission electron microscopy, light microscopy, fine-grained microstructure

1. INTRODUCTION

Constrained groove pressing (CGP) is a processing method (figure 1), in which a metal is subjected to an intense plastic deformation through repeated shearing and pressing (flattening) of plate. In 2001, Zhu et al. described an SPD method based on the repetitive corrugating and straightening (RCS) which is more known now as CGP (Zhu at al., 2001; Huang at al., 2001). This method comprises bending of a straight billet with corrugated tools and then restoring the straight shape of the slab with flat tools. The repetition of the process is required to obtain a large strain and desired structural changes.

The goal of the FEM modelling was to analyse the forming process with different specimens for different groove designs. The investigation focused on the distribution and amount of effective strain and the magnitude and changes of forming forces. The

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proposed alternatives were computed with the aid of the DEFORM 3D software package. The alternative, which showed most favourable results was tested experimentally.

The effectiveness of two-step successive groove and flat pressing (corrugation process) was examined with the aim to study the effect of pressing condition on the microstructural development and mechanical behaviour. The evolution processes of fine-grained structures and their grain boundary characteristics were investigated by means of light and transmission electron microscopy.

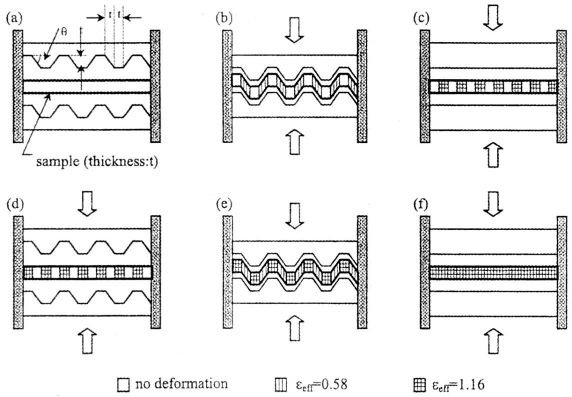

Fig. 1. A schematic illustration of CGP method: 1 pass consists of four strokes (b,c,e,f) with 180° rotation of the plate between the second and third stroke (c and e), resulting in fairly uniform strain introduced into the material.

2. SIMULATION INPUT PARAMETERS

In the following section, the parameters for the numerical simulation are listed. Several alternatives (table 1) were selected for investigation to assess the impacts of varying process parameters. These alternatives were designed to examine the impact of changed groove geometry (groove flank angle denoted as θ in figure 2, tool characteristic dimension t in figure 2) and specimen dimensions (thickness of specimen).

The desired parameters involved high introduced strain, uniform strain distribution and technically achievable forming forces. The difficulties lie in the presence of transition regions between the deformed and non-deformed segments of the plate and in distortion of the plate, which results in shifting the deformed regions towards the centre of the plate.

3. SPECIMEN

Model: plastic
Geometry: 3 alternatives: 70 x 30 x 8; 70 x 30 x 10; 70 x 30 x 13 [mm]
Material: 2 materials, data drawn from the DEFORM database
AISI 1015 (20 – 1100°C), forming temperature 400°C
Al-6063, COLD (20 – 250°C), forming temperature 20°C

4. TOOLS

Model: rigid
Geometry: 3 alternatives (groove flank angles of 38°, 45° and 52°), characteristic dimension of dies: 8 mm

Conditions
Shear: 0,15 (shear condition)
Tool motion: upper die: constant velocity of 10 mm/s

Table 1. Proposed investigation alternatives.

No. alternative	Material grade	Specimen thickness [mm]	Tool angle
1	AISI 1015	8	38
2	AISI 1015	8	45
3	AISI 1015	8	52
4	AISI 1015	10	38
5	AISI 1015	10	45
6	AISI 1015	10	52
7	AISI 1015	13	38
8	AISI 1015	13	45
9	AISI 1015	13	52
10	Al-6063	8	38
11	Al-6063	8	45
12	Al-6063	8	52
13	Al-6063	10	38
14	Al-6063	10	45
15	Al-6063	10	52
16	Al-6063	13	38
17	Al-6063	13	45
18	Al-6063	13	52

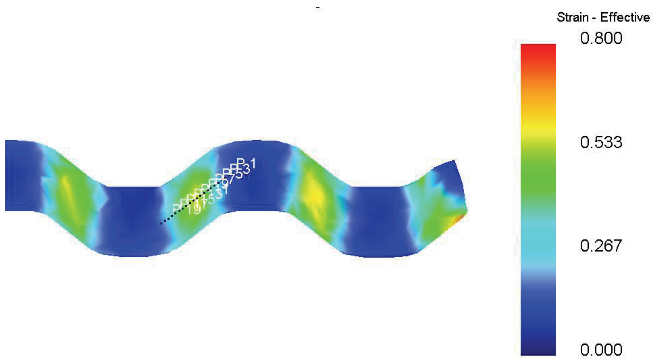

Fig. 2. Positions of points for evaluation of the effective strain.

5. EFFECTS OF THE SPECIMEN THICKNESS

The impact of the specimen thickness is most significant in terms of the strain distribution. The width of the intensive plastic strain zone is the most affected parameter, while the maximum magnitude of introduced plastic strain remains virtually constant. With increasing specimen thickness, the high-strain zone becomes narrower (figure 3). The forming force magnitude increases with the thickness of the specimen (figure 4).

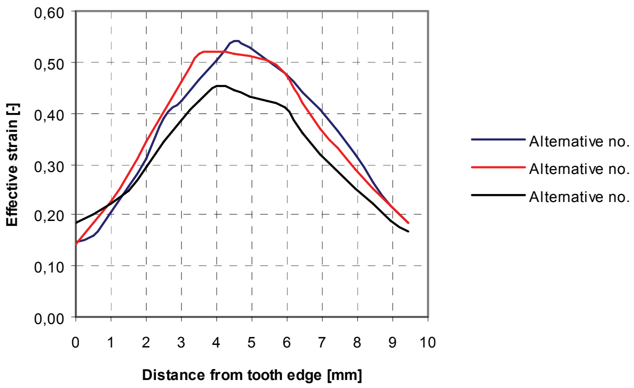

Fig. 3. Distribution of the effective strain in the specimen in transversal direction. The distance has been measured from the die tooth edge.

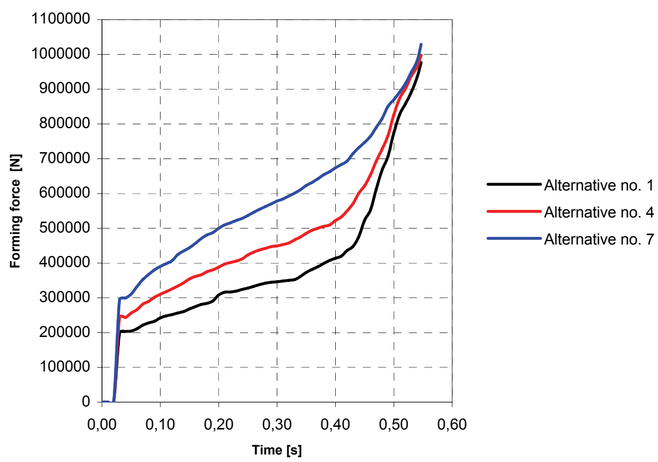

Fig. 4. Comparison of forming force magnitudes. Clearly, the higher specimen thickness, the higher the force.

6. EFFECTS OF THE GROOVE GEOMETRY

The effect of the tooth flank angle is most pronounced in terms of distribution and magnitude of introduced strain. With increasing flank angle, the introduced strain increases in the deformed segments of the specimen (figure 5). However, the width of the intensive plastic strain zone decreases, resulting in less homogeneous strain within the specimen. Strain non-homogeneity is undesirable, while there is the effort to introduce large strain into the material by many passes. The magnitude of the forming forces markedly affects the tool life. The forming force magnitudes do not change significantly with changing groove flank angles, being merely redistributed to greater tool displacement (figure 6).

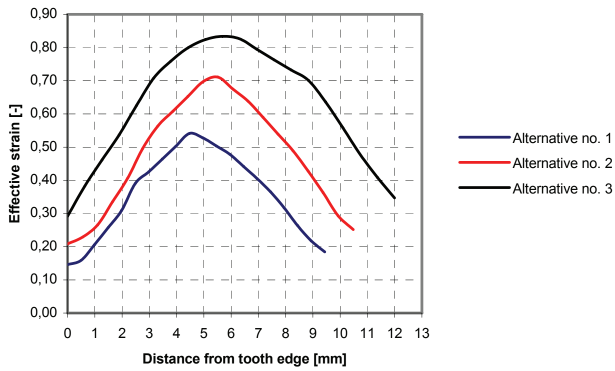

Fig. 5. Effective strain distribution in the transversal direction of the specimen. The distance has been measured from the die tooth edge.

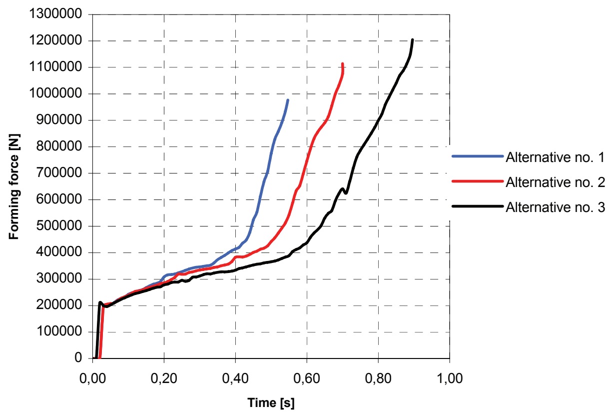

Fig. 6. Comparison of forming force magnitudes for different die groove angles as indicated in table 1.

7. COMPARISON OF ALTERNATIVES WITH IDENTICAL TOOTH HEIGHT/SPECIMEN THICKNESS RATIO OF 0.7

The comparison of effective strain and forming force is shown in figure 7 and figure 8.

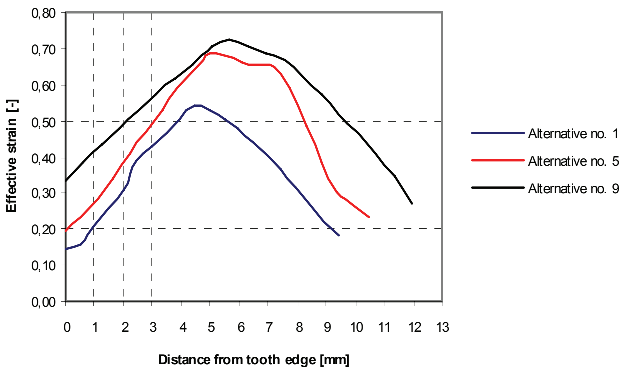

Fig. 7. Distribution of the effective strain in the specimen in transversal direction. The distance has been measured from the die tooth edge.

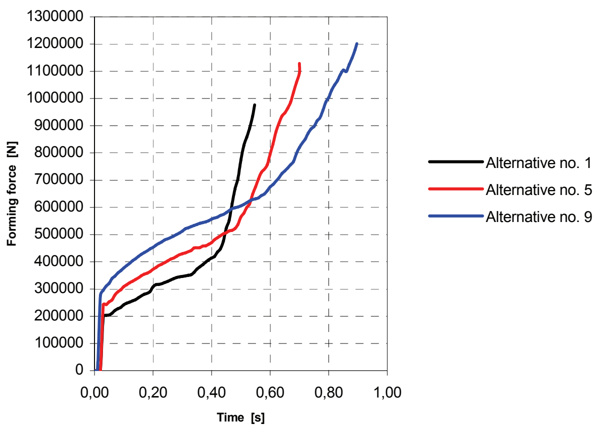

Fig. 8. Comparison of forming force magnitudes.

8. EFFECTS OF MATERIAL

The selection of material grade does not significantly affect the distribution nor the magnitude of introduced strain (figure 9). However, different forming resistance results in different forming forces (figure 10).

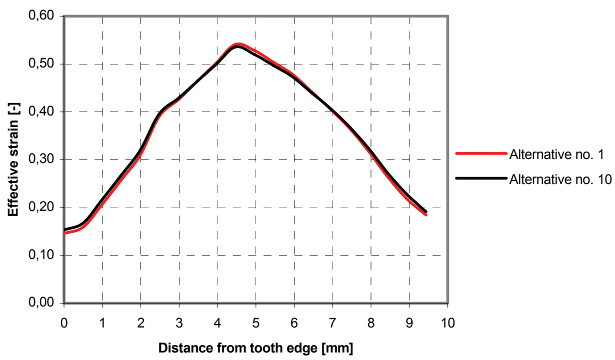

Fig. 9. Distribution of the effective strain in the specimen in transversal direction. The distance has been measured from the die tooth edge.

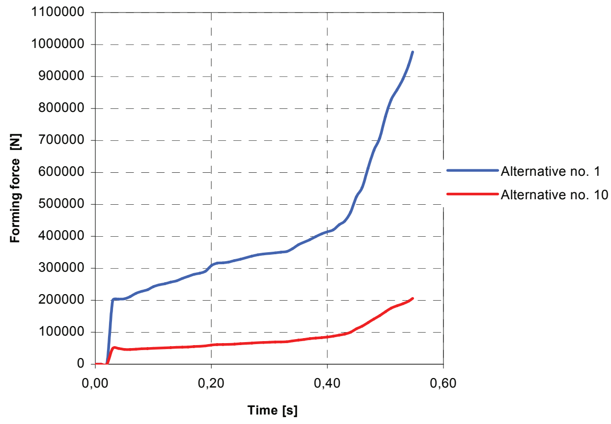

Fig. 10. Comparison of forming force magnitudes.

9. NUMERICAL SIMULATION RESULTS

The calculations have shown the differences in distribution and magnitude of effective strain between the experimental alternatives. Evidently, the most pronounced effects upon the strain distribution are produced by the tool design (groove flank angle). The effects of different experimental materials can be seen in the forming force magnitude.

Results of the numerical modelling clarified the forming process and enabled the selection of optimum tool shapes and parameters for the experiment.

The following parameters have been selected for the experimental processing:

– 45° angle of die groove flank – as in the standard technique – this represents a compromise between the desired high introduced strain and corresponding required forming force. Moreover, high tooth angle results in increasing non-homogeneity of the strain,
– pure Al (99.99%) was selected as the experimental material in order to decrease forming forces and friction for the initial experiment and to prevent damage to the tools,
– 7 mm thickness of specimen was chosen and equal characteristic dimension of the tool to enable the control over the strain distribution and to avoid excessive forming forces, as the forming force grows with sample thickness. The original parameter of 8 mm was thus decreased due to limited working space of the used hydraulic press.

10. EXPERIMENTAL PROCEDURE

Commercial purity aluminium was supplied as cold rolled 10 mm thick plate. Prior to CGP pressing, the plate was annealed at the temperature of

250°C for 1.5 h in order to obtain the recrystallized structure with large grains of several hundreds of micrometers size. The experimental specimens were milled from the plate. The light microscopy (LM) was used to observe the microstructure of the initial plates.

Three plates were used for experiments: one was deformed with a single stroke with grooved dies, the second one was deformed and flattened, and the third one underwent a complete pass with four strokes. The microstructure investigation was performed with the aid of transmission electron microscopy.

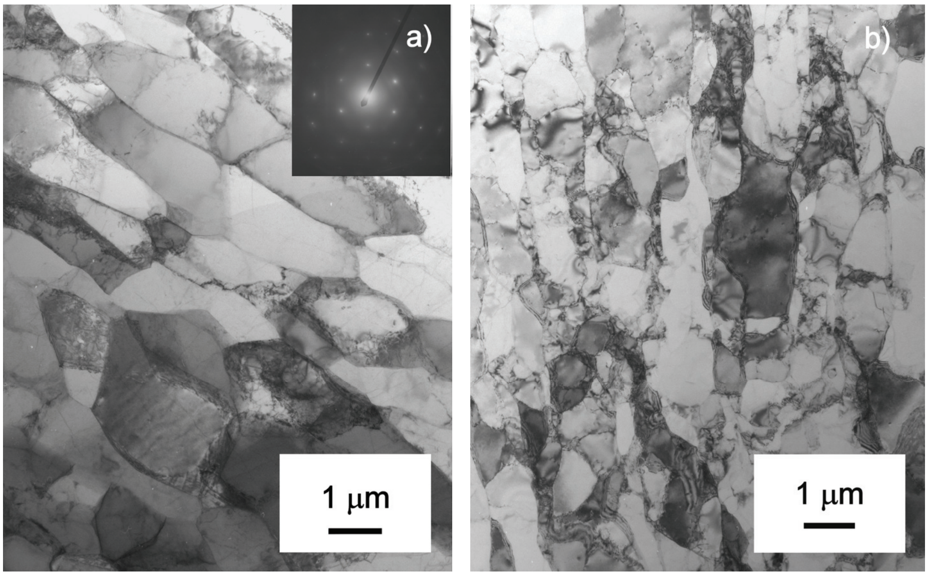

Fig. 11. *a) TEM micrograph of subgrain structure formed in the flat area of the grooved plate. b) TEM micrograph of subgrains microstructure after second pressing with grooved dies.*

As evidenced by numerical simulation (figure 2), slight tensile stress is acting on the flat non-deformed segments during bending of the plate. This is documented by figure 11 a) showing the microstructure of a non-deformed segment in the plate upon single stroke. The structure consists of elongated and/or equiaxed subgrains, and dislocation cells. The material in this region has been affected by some amount of plastic deformation and it cannot be referred to as an "undeformed" area.

The microstructure after second groove-shape formation, upon the plate was rotated 180°, formed in the sheared segment is documented in figure 11 b). The micrograph shows the fine subgrain structure, where former longer elongated subgrains are fragmented to smaller more equiaxed subgrains. Inside this microstructure, nucleated along former subgrains a new smaller nuclei of polygonized grains, with size about 1 μm and less are found.

11. CONCLUSIONS

The calculation has shown the differences between the alternative forming configurations in terms of the distribution and amount of effective strain. The computation results were used as a basis for design of optimum-shaped tools and verifying the technological process.

It was found that although higher groove flank angle results in higher introduced strain, it also reduces the homogeneity of the strain. Since using more passes can increase the amount of introduced strain, the strain homogeneity becomes the prevailing criterion. Low specimen thickness was selected with respect to limited available forming force of the laboratory hydraulic press. Selection of the experimental material was guided by the effort to reduce damage to first experimental set of forming tools and to more easily observable microstructure changes in the single-phase microstructure. The optimum alternative has been experimentally tested.

The results show that the Constrained Groove Pressing with one completed pass resulted in formation of non-uniform finer microstructures with some new grains formed by intensive deformation and dynamic recrystallization process. The presence of low tensile and compressive strain in flat segments of specimens, resulted as well in grain refining process, as suggested by numerical simulation, has been confirmed by transmission electron microscopy observation. However, higher number of passes is required to further homogenize and refine the microstructure.

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MODELOWANIE NUMERYCZNE PROCESU KUCIA W MATRYCY ZE ZBIEŻNYMI ROWKAMI Z WYKORZYSTANIEM PAKIETU DEFORM 3D

Streszczenie

Kucie w matrycy ze zbieżnymi rowkami (CGP) jest jednym z wielu procesów przeróbki plastycznej, który wykorzystywany jest przede wszystkim do przygotowania drobnoziarnistej struktury materiałowej. Za pomocą tej technologii możliwe jest wytwarzanie wielu drobnoziarnistych materiałów o dużej objętości. Metoda elementów skończonych może być wykorzystana do weryfikacji parametrów projektu narzędzia w celu optymalizacji kształtu narzędzi CGP oraz parametrów procesu. Dzięki temu możliwe jest uzyskanie znaczących informacji na temat wpływu kształtu narządzi, właściwości materiałowych oraz tarcia na płynięcie materiału podczas odkształcenia. Niniejszy artykuł przedstawia wykorzystanie modelowania numerycznego w celu analizy procesu przeróbki dla matryc o różnym kształcie wyżłobień, zróżnicowanej grubości próbki oraz dla dwóch różnych materiałów (stal oraz stop aluminium). Otrzymane rezultaty pokazują, iż w wyniku zastosowania metody CGP otrzymano niejednolitą strukturę drobnoziarnistą z zarodkującymi nowymi ziarnami, które powstały jako efekt silnego odkształcenia oraz procesu dynamicznej rekrystalizacji.

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