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RADIAL EXTRUSION OF GEAR LIKE COMPONENTS – NUMERICAL ANALYSIS AND EXPERIMENT

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Original scientific paper
In this paper investigations of cold radial extrusion of gear-like components are presented. Focus has been placed on load requirement, metal flow during extrusion, die filling and strain distribution within the deformation zone. Two different geometries of gear-like components were considered: with straight radial, straight tapered and with straight parallel flank profile. Extrusion load exhibits three different phases: initial steep rise, gradual load development (steady extrusion state) and rapid load rise at the end of the process when corner filling takes place. Material flow is characterized by occurrence of "double barrelling" of free profile surfaces due to friction which exists at the die-material surfaces. The highest strain values were observed in the root of the teeth while in the middle part of the workpiece lower strain values appear. In numerical FE analysis DEFORM 3D, Ver. 10.2 software was employed. For the experimental investigation special tool has been designed and made. Aluminium billets were applied.

Keywords: *die filling, radial extrusion, strain distribution*

Radijalno istiskivanje ozubljenih elemenata – numerička analiza i eksperiment

Izvorni znanstveni članak
U ovom radu prikazana su istraživanja hladnog radijalnog istiskivanja ozubljenih elemenata. Fokus je stavljen na potrebnu deformacijsku silu, tečenje materijala tijekom procesa deformiranja, popunjavanje alata i raspored deformacija unutar obratka. Analizirane su dvije različite geometrije ozubljenih elemenata. Deformacijske sile pokazuje tri različite faze: početnu fazu s naglim porastom sile, fazu umjerenog rasta sile i ponovo nagli porast sile na kraju procesa kada se odvija popunjavanje polumjera zaobljenja u alatu. Na slobodnim površinama obratka odvija se dvostruko naburičavanje uslijed djelovanja trenja na kontaknim površinama alata i obratka. Najviše vrijednosti deformacije su u korijenu zuba, dok su najniže vrijednosti u središtu obratka. Numerička analiza metodom konačnih elemenata izvedena je programom DEFORM 3D, Ver. 10.2. U cilju izvođenja eksperimenta konstruirani su specijalni alati. Korišteni su uzorci od aluminija Al99.5.

Ključne riječi: *popunjavanje alata, radijalno istiskivanje, raspodjela deformacija*

1 Introduction

Cold extrusion and forging of gears and gear-like components is increasingly gaining importance because of its advantages over classical machining methods. Main advantages are: better material and energy utilization, enhanced mechanical properties and better surface finish of extruded components as well as considerably higher productivity rates.

One of the most frequently used methods of producing gears by metal forming is radial extrusion, often referred to as lateral extrusion, side extrusion, transverse extrusion or injection forging. In this process, a cylindrical billet retained in a die with the profiled cavities is forced by an axial punch to flow radially into these cavities. Based upon this principle, a number of different variants of radial extrusion have been developed.

Research into the radial extrusion of gears has been reported in a number of papers. An extensive review which includes different process configurations, current research efforts and possible applications was given in [1]. The authors investigated three different injection forging configurations: with a solid billet, with a tubular billet and with a tubular billet assisted by inner pressure.

A two-step precision radial forging technology of spur gears was proposed in [2]. The authors claimed that the accuracy of the new method was comparable with the accuracy of machining. Research into radial extrusion of hollow gear–shafts was reported in [3]. The authors used polymers as a pressurized medium in radial extrusion of tubular components.

Theoretical analyses of radial extrusion of gear using Upper Bound method are reported in [4], [5] and [6]. The calculated fields of velocity were verified experimentally. New, improved analytical interpretation of the velocity fields in different workpiece zones for UBET analysis was proposed.

Results of FE simulations and experiments of hot forging of spur bevel gears made from magnesium alloy were presented in [7]. The influence of various shapes of preform and dies on the process parameters was analysed using commercial FE software and the optimum preform shape was evaluated.

Analysis of strain distribution, in the cold radially extruded gear-like component, based on the numerically calculated distribution of grain size in the meridian plane of the component, was reported in [8]. Results of numerical simulations showed fair agreement with experimentally obtained strain distribution.

The main limiting factor in the application of cold radial extrusion for the gear-type components is high stress to which the die is subjected during the operation. In order to reduce the die loading so called "divided flow method" was proposed [9]. The method consisted in introducing a flow relief hole in the billet and flow relief axis in the die. The main idea was to reduce working load by causing an inward material flow. The process was analysed theoretically using the Upper Bound method. Results of experiment, which confirmed theoretical solution, were presented in [10].

Lateral extrusion of 3D component was analysed by numerical simulation (FE) and experimentally in [11]. Impact of major process parameters, such as initial billet geometries, gap height and friction conditions on the required load and material flow has been investigated. In experiments lead billets were used.

This paper presents results of the numerical analysis and experimental investigation of the radial extrusion of gear-like components with 6 teeth. Two shapes of the teeth, shown in Fig.1, were considered: type A with a straight radial flank profile and type B with a straight tapered flank profile. Values of the parameters shown in Fig.1 were as follows:

- angles $\alpha = \pi/6$, $\beta = \pi/12$, $\psi = \pi/6$
- inner radius $r_0 = 14$ mm
- outer radius $r_1 = 17$ mm
- tooth height $h = 15,8$ mm.

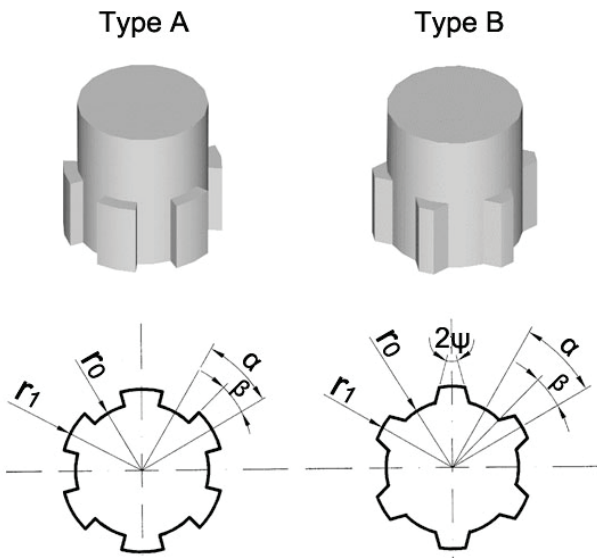


Figure 1 Geometrical parameters for two types of gear-like components

Three aspects of the process were examined: load-stroke characteristics, die filling and strain distribution in the extruded component. Numerically obtained results were compared with experimental results.

2 Numerical simulation

Numerical analysis of two different gear-like components (type A and B) was conducted using finite element (FE) method. Geometrical parameters and properties of the gear material (Al 99.5) are given in Fig. 1 and Tab. 1, respectively.

Table 1 Material properties used in FE models (Al 99.5)

Young's modulus	69 000 MPa
Yield stress	$R_{p0,2}$ = 82,3 MPa
Work hardening	$\sigma = 152,49 \cdot \varphi^{0,292}$ MPa
Poisson's ratio	0,3

Stress-strain curve has been obtained in a compression test using Rastegaev's test specimens [12].

Simulations were performed using DEFORM 3D, Ver.10.2 software. A full 3D model was created. The workpiece material was modelled as an isotropic elastic plastic material with the von Mises yield criterion. A cylindrical billet with dimensions Ø28 × 40 mm was used in simulations. Solid linear tetrahedral elements were used to create the mesh. A total of 123 310 elements were used to model the billet. The tools were modelled as rigid bodies. Coulomb friction between the work material and the die was assumed with a friction factor 0,12. As a result of FE simulation a load-stroke signature, die filling development and strain distribution within the forming zone for different process stages (different extrusion loads) for two gear types (A and B) have been identified.

3 Experimental investigation

In order to conduct experimental investigation, special tooling was designed and made [5]. Die inserts were made by EDM machining. Process parameters (workpiece geometry, material properties, friction, speed) were equal to those used in numerical simulation. Experiments were performed on a hydraulic Sack&Kiesselbach press at room temperature with a speed of 0,3 mm/s. Initial dimensions of the aluminium billets were those used in simulations i.e. Ø28 × 40 mm.

Cylindrical billets were lubricated with oil and placed into the die. After assembling the billet and the die, extrusion load was applied to the punch with flat head. Material was forced to flow radially into the geared profile at die insert placed at the bottom of the die. During extrusion load and punch stroke were recorded. Photographs of the two different gear types and corresponding die inserts are given in Fig. 2.

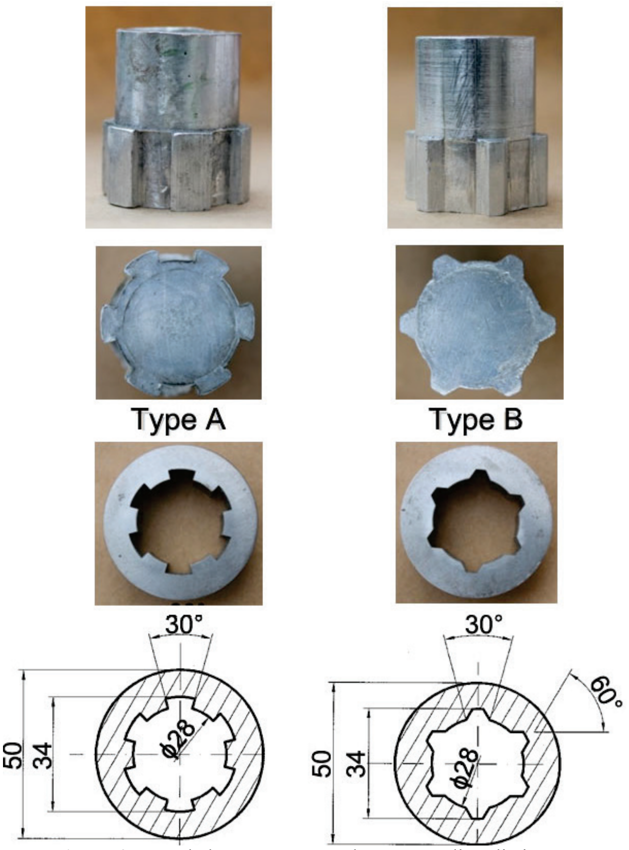


Figure 2 Extruded components and corresponding die inserts

4 Results and discussion

4.1 Load-stroke characteristics

Numerically predicted load-stroke diagrams for two component types are given in Fig. 3. Differences between punch strokes are due to the fact that each gear-type profile has different volume; bigger volume has component type A and smaller type B.

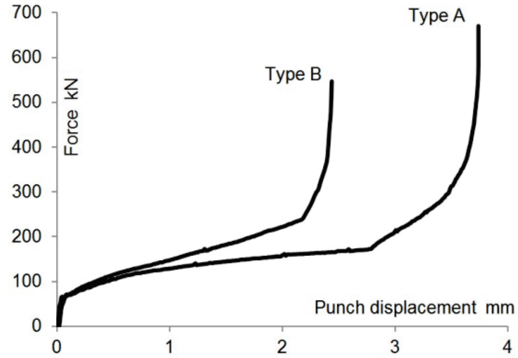


Figure 3 Load-stroke characteristics for gear types A and B obtained by FE simulation

Load-stroke signatures for both gear types clearly show existence of three different phases. At the beginning of the process, load rises sharply due to elastic deflection of the workpiece. Later, in the intermediate phase a gradually raising slope of the load can be observed. In this phase intensive material flow into the gear profile takes place. Second phase ends when material reaches the outer radius of the gear profile. From this point on rapid load increase can be observed. This is, so called, corner filling phase. The results show that higher load occurred in case A (gear with straight radial flank profile) than in case B (gear with straight tapered flank profile). Comparison of the load-stroke curves obtained experimentally and by numerical simulation for both gear types is shown in Figs. 4 and 5.

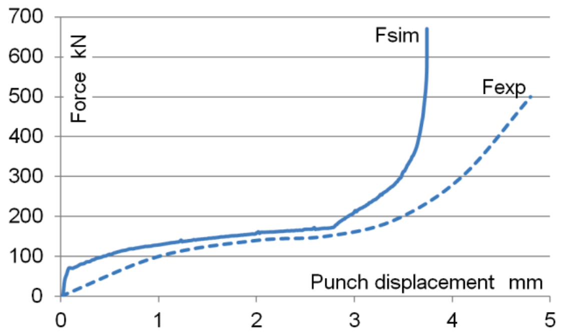


Figure 4 Load-stroke diagrams for type A

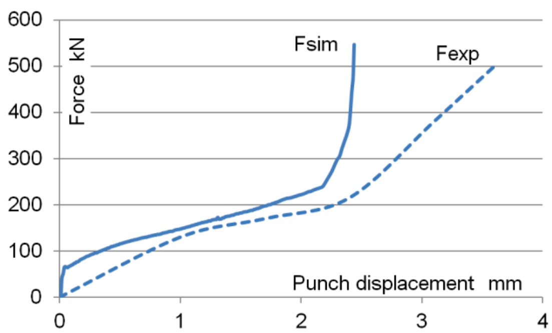


Figure 5 Load-stroke diagrams for type B

The comparative diagrams show that there is a relatively good agreement between numerically and experimentally obtained results for both gear types, except in the final, corner filling phase when certain difference can be observed. In this phase numerically predicted load is slightly higher than experimental. Also, for the same load experimental stroke is somewhat longer than numerical. This could be attributed to elastic deformation of the die, and the press as well as extrusion of the flash through the clearance between the punch and the die.

4.2 Die filling

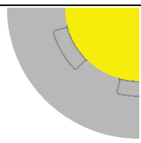
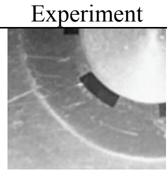
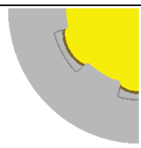
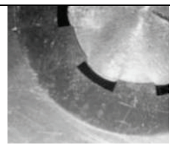
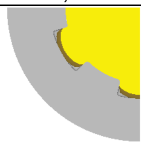
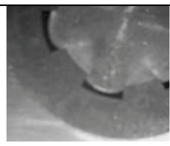
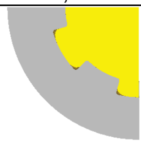
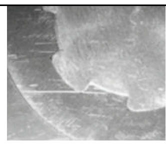
In order to analyse die filling progress (workpiece material which entered the die gear profile), a measure of the degree of die filling was introduced as:

$$DF = \frac{V}{V_C}, \quad (1)$$

V – volume of the material already pushed into the die (current punch displacement x slug cross section)
V_C – volume of the material required to fill completely die profile (final punch displacement x slug cross section).

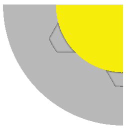
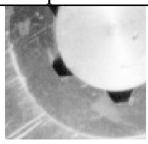
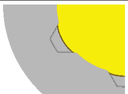
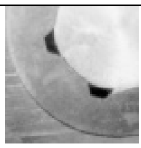
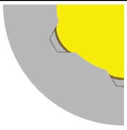
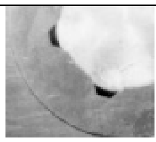
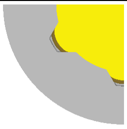
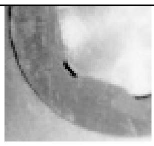
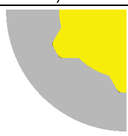
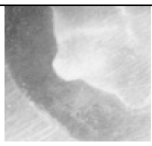
Degrees of die filling in different process phases (different extrusion loads) obtained numerically for both types of gear-like component are presented in Tabs. 2 and 3. Besides that, photographs of die filling for corresponding load, obtained experimentally, are also given in Tabs. 2 and 3.

Table 2 Degrees of die filling - extrusion of gear-like component type A

Load / kN	FE	Experiment
0	 0 %	
150	 45,2 %	
190	 76,7 %	
500	 99,4 %	
670	 100 %	

In Fig. 6, the interdependence between the degree of die filling and extrusion load for both gear-types is numerically established. As it can be seen from Fig. 6, die filling curves for both gear types are very similar. Almost 85 % of the profile is filled up in quasi steady state phase with the relatively small load (≈ 200 kN) whereas filling of the complete profile (the remaining 15 %) requires significantly higher load.

Table 3 Degrees of die filling - extrusion of gear-like component type B

Load / kN	FE	Experiment
0	 0 %	
130	 29,5 %	
170	 53,3 %	
215	 77,9 %	
500	 100 %	

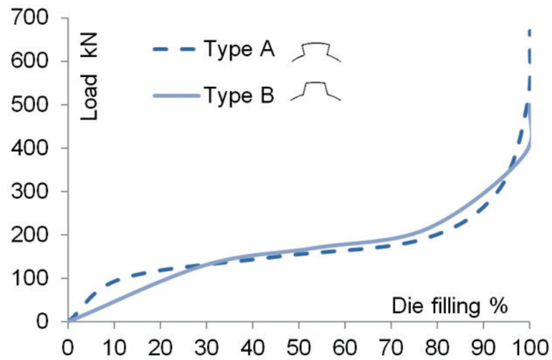


Figure 6 Numerically obtained die filling – extrusion load relationship

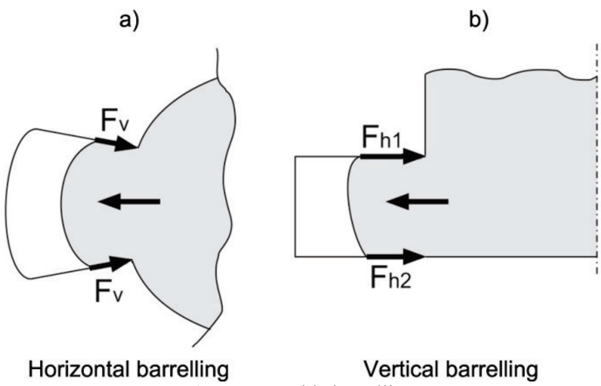


Figure 7 Double barrelling

Flow pattern during extrusion is characterized by non-uniformity of the free surface profile in vertical and horizontal plane, e.g. occurrence of "double barrelling". Horizontal barrelling takes place as a result of friction between workpiece material and vertical surfaces of the die (F_v in Fig. 7a). Vertical barrelling occurs due to friction which exists between workpiece material and bottom and upper contact surface of the die (F_h in Fig.7b).

Vertical barrelling is not symmetrical with respect to horizontal (equatorial) section of the tooth (Fig.7b). This means that material at the top of a tooth moves in radial direction with higher velocity than material at the bottom. This can be explained by different values of friction forces at the lower and upper contact surface between die and material ($F_{h1} \neq F_{h2}$). This phenomenon has been also reported in [6], [13] and [14]. Only in the last stage of the process both types of barrelling are eliminated, i.e. die corners are filled up.

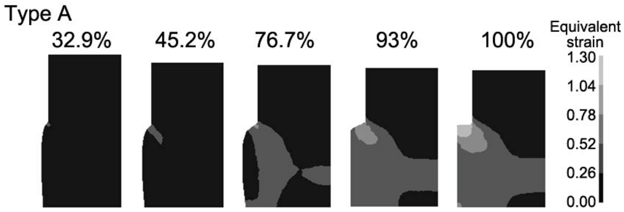


Figure 8 Progress of die filling for A-type components

4.3 Strain distribution

Development of equivalent strain (φ_e) within extruded gear profile in different process phases, with the percentage of die filling in every phase is given in Fig.8. Presented strain pattern indicates that in the beginning of the process the highest strain occurs in the root of the gear profile while in the later process stages a horizontal material flow from the inner part of the workpiece to the gear profile takes place.

Higher values of strain exist in the middle part of the specimen, where material flows horizontally into the gear cavity. Absolutely highest strain values take place in the upper and lower corners of the gear profile.

In gear type B (Fig. 9) lower amount of workpiece volume is involved in the intensive material radial flow.

Higher strain values exist only in the region which is relatively near to the gear profile. Again, as in previous two cases, highest strains occur at the upper and lower corners.

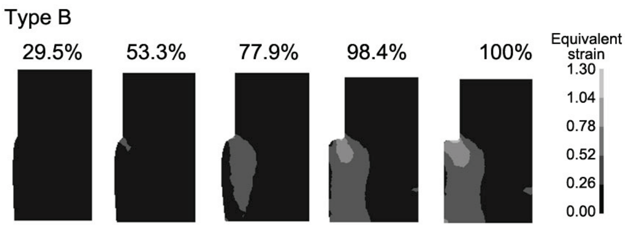


Figure 9 Progress of die filling for B-type components

Numerically obtained distribution of equivalent strain (φ_e) in the meridian (vertical) plane at the end of the process, for both gear types, is given in Fig. 10. As it can be observed, flow pattern for the gear of type A has a large region with low strain located near the surface in contact with upper and lower die.

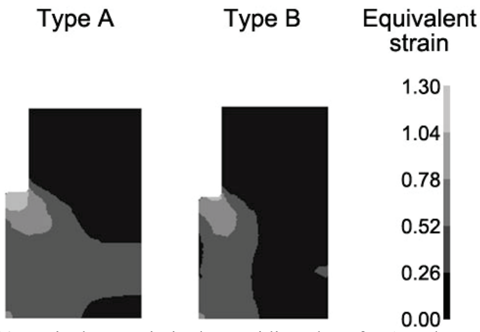


Figure 10 Equivalent strain in the meridian plane for A and B gear types at the end of extrusion

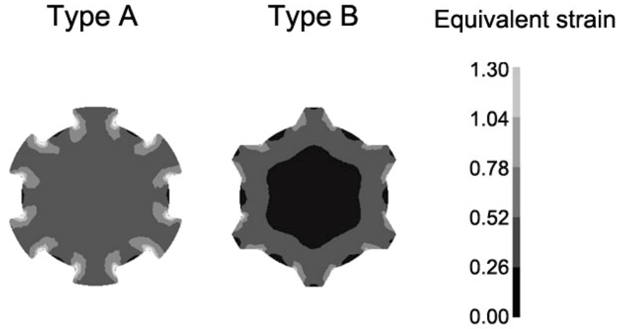


Figure 11 Equivalent strain in a cross section half the height of the tooth

Final strain distribution at the horizontal cross section half the height of the tooth is shown in Fig. 11. As seen in this figure, the highest strain values in both gear types occur at the root of the teeth, whereas in the middle part of the cross section lower values of equivalent strain appear. This is especially the case in gear type B where in the centre part of the workpiece deformation can hardly be observed.

5 Conclusions

Cold radial extrusion of gear-like components has been investigated numerically and experimentally. Based on the obtained results, the following conclusions can be formulated:

- Load-stroke diagrams indicate that three phases of the process could be distinguished. During the first phase elastic deflection and upsetting of the billet to fill the cavity of the chamber retaining the billet takes place. The second phase corresponds to filling of the gear profile while in the third phase filling of the profile corners is accomplished. In the last phase a steep load rise is observed.
- Magnitude of the experimental load (F_{exp}) is in good agreement with the numerical prediction (F_{sim}). However, due to elastic deflection of the die and press, which were not taken into account in numerical analysis, a shift along displacement axis occurs between F_{exp} and F_{sim}.
- Load-die filling curves for both gear-types have a similar form. More than 80 % of the profile is filled in a quasi-steady extrusion stage, with a gradual rise of load.
- Barrelling of the gear teeth, in horizontal and vertical plains, that was observed in the calculated shapes has been confirmed experimentally.
- Distribution of equivalent strain (φ_e) within the gear profile is similar for both gear types. The highest strain values are observed in the root of the tooth while the lowest strain exists in the central part of the billet.

It is proposed that the current research is extended to cover other types of gears with different number of teeth, materials and geometries. In the numerical analysis, elastic deformation of the billet, dies and press should be taken into account. In this way more realistic numerical results would be obtained and discrepancy between experimentally obtained and numerically predicted load-stroke signatures might disappear.

Acknowledgement

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6 References

[1] Balendra, R.; Qin, Y. Injection forging: engineering and research. // Journal of Materials Processing Technology. 145, (2004), pp. 189-206.
[2] Choi, J. C.; Choi, Y. Precision forging of spur gears with inside relief. // International Journal Machine Tools & Manufacture. 39, (1999), pp.1575-1588.
[3] Ma, Y.; Qin, Y.; Balendra, R. Forming of hollow gear-shafts with pressure-assisted injection forging (PAIF). // Journal of Materials Processing Technology. 167, (2005), pp. 294-301.
[4] Chitkara, N. R.; Kim, Y. J. Near-net shape forging of a crown gear: some experimental results and an analysis. // International Journal of Machine Tools & Manufacture, Design, Research and Application. 41, (2001), pp. 325-346.
[5] Plancak, M.; Vilotic, D.; Skakun, P. A study of radial gear extrusion. // International Journal of Forming Processes. 6, 1(2003), pp. 71-86.
[6] Altinbalik, T.; Can, Y. An experimental study of lateral extrusion of splines. // Materials & Design. 27, (2006), pp. 727-734.
[7] Liu, J.; Cui, Z. Hot forging process design and parameters determination of magnesium alloy AZ31B spur bevel gear. // Journal of Materials Processing Technology. 209, (2009), pp. 5871-5880.
[8] Skunca, M.; Skakun, P.; Keran, Z.; Math, M.; Sidjanin, L. Relations between numerical simulation and experiment in closed die forging of a gear. // Journal of Materials Processing Technology. 177, (2006), pp. 256-260.
[9] Ohga, K.; Kondo, K. Research on precision die forging utilizing divided flow, first report, Theoretical analysis of processes utilizing flow relief-axis and relief-hole. // Bulletin of the JSME. 25, 209(1982), pp. 1828-1835.
[10] Ohga, K.; Kondo K.; Jitsunari T. Research on precision die forging utilizing divided flow, second report, Experimental study of processes utilizing flow relief-axis and relief-hole. // Bulletin of the JSME. 25, 209(1982), pp. 1836-1842.
[11] Jafarzadeh, H.; Faraji, G.; Dizaji, A. F. Analysis of lateral extrusion of gear-like form parts.//Journal of Mechanical Science and Technology. 26, 10(2012), pp. 3243-3252.

[12] Vilotic, M.; Mandic, V.; Plancak, M. UBET analysis, finite element simulation and experimental investigation of backward extrusion. // Journal for Technology of Plasticity, 29, 1-2(2004), pp. 85-97.
[13] Chitkara, N. R.; Bhutta, M. A. Shape heading of splines and solid spur gear forms: an analysis and some experiments. // International Journal of Mechanical Sciences, 43, (2001), pp. 1073-1106.
[14] Narayanasamy, K.; Baskaran, R.; Arunachalam, S.; Murali Krishna D. An experimental investigation on barrelling of aluminium alloy billets during extrusion forging using different lubricants. // Materials and Design, 29, (2008), pp. 2076-2088.

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