Journal of Materials Processing Technology 177 (2006) 256–260

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

Relations between numerical simulation and experiment in closed die forging of a gear

M. Skunca [a,*], P. Skakun [b], Z. Keran [a], L. Sidjanin [b], M.D. Math [a]

[a] *Chair of Metalforming, Faculty of Mechanical Engineering and Naval Architecture, Department of Technology, University of Zagreb, Ivana Lučića 5, HR-10000 Zagreb, Croatia*

[b] *Institute for Production Engineering, Faculty of Technical Sciences, University of Novi Sad, V. Perica Valtera 2, 21000 Novi Sad, Serbia and Montenegro*

Abstract

The improvement of specific metal forming technologies, nowadays includes the use of numerical program packages. One such technology is the radial extrusion of gears and gear-like components in the cold state. This technology is known for its high productivity, achievable high specific strength and low cost per part produced. Improvements of such high technology products can be only achieved by the detailed numerical analysis. Since there is a large number of programs available, it is necessary to carry out the comparisons between the experiment and simulation. One of the commonly used methods is the comparison of experimentally and numerically obtained load–displacement diagrams. Although significant, good accordance of such load–displacement diagrams is insufficient proof of having a good numerical model. In this paper an additional, non-conventional method is used to assess the strain distribution within the workpiece. Though the experimentally obtained strain field was used as a reference, the numerically obtained strain distribution pointed to the highly stressed points, giving a direction to the further experimental examination of strain distribution in greater detail. The result is an improvement of both experiment and numerical model. In the simulation there are inherent non-linearities coming from geometry, strain hardening and friction. In the determination of the strain distribution, a very complex phenomenon of restoration was used. The combination resulted in a model of the radial extrusion that can be used in numerical simulations of similar metal forming processes.

Keywords: Radial gear extrusion; Numerical simulation; Finite elements method

1. Introduction

Cold forging became a widely used technology in automotive industry. High productivity, accuracy and absence of prerequisite material heating, made it suitable in manufacturing of diverse machine parts. Cylindrical spur gears [1–8], bevel gears [9–12], helical gears [13–15], cross groove inner races [16–18] and many other, even more challenging geometries, are produced within the frames of this technology.

Problems concerning cold forging have multiplied themselves same way as the area of application did. Mechanical properties depending on strain distribution within the workpiece, friction, predicted die life and forming load are just some of the questions that need more precise answer. An absence of material heating, results in large strains and stresses in both tool and workpiece. Detailed preparation of cold forging is necessary to avoid defects in product and extend the die life.

Commercially available packages [19] play a significant role in preparation and optimization of the metal forming processes in cold state. Key parameters like plastic strain distribution, that cannot be measured, have to be assumed. Finite element method gives an opportunity to make an interpolation/assumption of the variables of the interest. In this paper, MSC.Marc Mentat 2005r2 is used to perform a 3D R–P flow analysis of cold forging of the bevel gear with the straight tapered flanks.

Finite element method (FEM) based on virtual work principle was used since it has found a wide area of application in simulations of diverse metal forming operations. Reasons to this are quite simple; intuitive division of continuum into smaller parts as firstly proposed by Courant, and secondly application of constitutive laws of the continuum mechanics to the engineering problems. Together with Lagrangian approach it covers a wide range of forming problems.

* Corresponding author. Tel.: +385 01 61 68 222; fax: +385 01 61 56 940.
E-mail address: mskunca@fsb.hr (M. Skunca).

0924-0136/$ – see front matter
doi:10.1016/j.jmatprotec.2006.04.061

Reliability of the numerical simulations cannot be taken for granted. Not since they include three great areas of the research: continuum mechanics, numerical analysis and computer technology. Immense number of complex notions coming from the combination of these three areas, imposes a need to have at least one experimental criteria to evaluate the used numerical program package within the technology of cold forging.

Force–stroke diagram and strain distribution were used as two different comparison criteria between MSC.Marc Mentat 2005r2 simulation and the experiment.

2. Tooling

Experimental basis was taken as a reference to estimate the created FEM model and the used program. A tooling for radial gear extrusion was designed and made as shown in Fig. 1. Modular construction with shrink fitted dies shows a great flexibility of cold forging tool. Minor changes like replacement of the die insert, enables the production of similar gear geometries as it was performed in Ref. [20].

Force and displacement transducer incorporated in hydraulic press resulted in the force–stroke diagram shown in Fig. 5. It was used as a first simulation–experiment comparison criterion. The aim was to obtain a relatively good force–stroke overlapping, reasonable calculation time and explainable numerical behaviour of the simulation. Mentioned was accomplished with low order tetrahedral element type. During simulation remeshing was performed to repair severely deformed mesh.

3. Numerical model

Simulation was performed in MSC.Marc Mentat simulation package. Although Marc is written in Fortran, it was used as a closed source code and all the preprocessing was done in Mentat Open GL. Limitations coming from this kind of approach are encompassed by respectable stability and ability to successfully deal with models consisting up to 50,000 nodes without domain decomposition. In other words it was able to deal with 200,000 linear and 50,000 parabolic elements on a single computer (2 Gb memory required) under XP Windows.

Due to the axial symmetry of the gear, simulation was performed on one-twelfth of the geometry (Fig. 2). This increased the element resolution to 0.7 mm and resulted in 5 h long calculation time for a simulation with friction modelling. Secondly, mesh coarsening towards the axis of symmetry could have additionally shortened the calculation time. This was omitted in order to achieve uniform element mesh along the horizontal plane where the comparison of strain distribution was to be made.

Boundary conditions were set by the use of axisymmetric planes since global remeshing was performed six times during the simulation. Within 76 increments 1248 Newton–Raphson cycles were performed. Residual force checking was used as a criterion of proceeding to the next increment. Conditioning number of the global stiffness matrix proved to be satisfying since singularity ratio remained within the desired interval [23].

As already denoted R–P flow formulation was used to model finite strain plasticity of commercially pure aluminium. Updated Lagrange procedure was used to set and solve equilibrium equations in current state. Written in short form, a global stiffness equation is used:

$$\boldsymbol{K}\boldsymbol{v} = -\boldsymbol{f} \qquad (1)$$

where $\boldsymbol{K}$ is the stiffness matrix, $\boldsymbol{f}$ the nodal load vector and $\boldsymbol{v}$ is the nodal displacement vector.

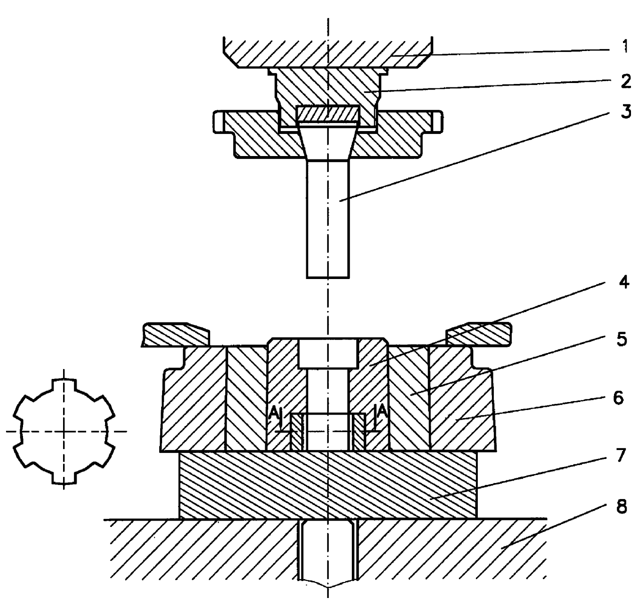

Fig. 1. Schematic representation of tooling: (1) upper plate, (2) punch holder, (3) punch, (4) replacable die insert, (5) inner ring, (6) outer ring, (7) lower plate and (8) hydraulic 6300 kN press.

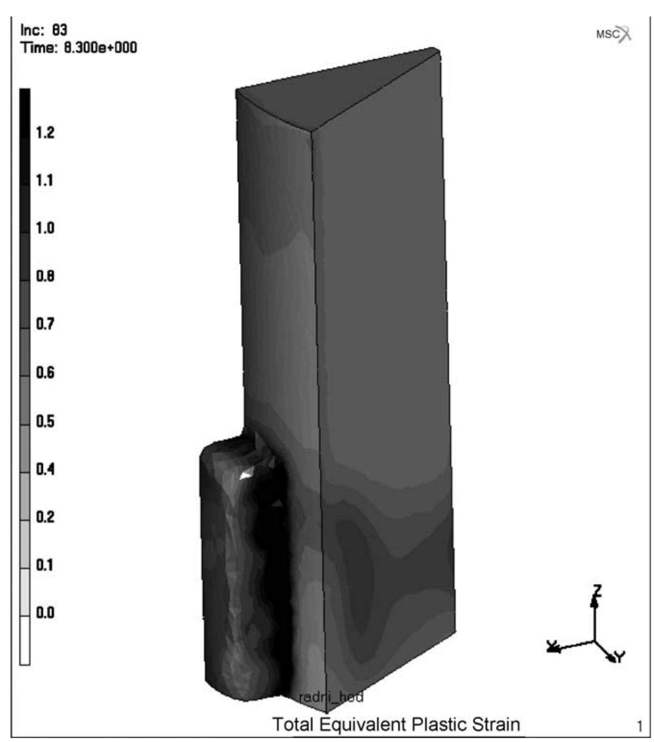

Fig. 2. One-twelfth of the gear simulated with 27,000 finite elements.

Finite strain plasticity with additive decomposition of strain rates, adequate for R–P flow analysis [23] resulted in a force–stroke diagram and strain distribution shown in Figs. 5 and 4, respectively. Due to the overall complexity and size of the FE model, the simplest, constant time loading scheme was used.

The element used was a low order (linear), 4 + 1-noded, isoparametric, three-dimensional, tetrahedron, using Herrmann formulation. Incompressibility was imposed by means of Lagrange multipliers since used element has an extra pressure variable as the multiplier.

Flowchart was assigned to the model after Ref. [21]. Linear interpolation of the flow data was used in order to save the processor time as much as possible.

All the objects in simulation except the aluminium billet were modelled as rigid bodies. Reasonable calculation time of 5 h enables the consideration of converting some parts of the closed die into finite element mesh. In that case elastic body division as proposed in Ref. [22] should be considered to minimize the number of elements and calculation time.

Friction, besides geometry and strain hardening, as a third source of non-linearity has been included through shear model. Used friction model based on the nodal stresses, limited the amount of friction coming from plastic deformations, but required the stress recovery at the end of each increment. This prolonged calculation time and resulted in premature termination of the simulation, as it can be seen from the force–stroke diagram. Simulation stopped after 76 increments due to the errors in stress recovery.

Therefore, an extra simulation was performed without friction. Result is complete fulfillment of the gear cavity and steep load rise at the end of the force–stroke diagram coming from the simulated die corner filling.

Residual force convergence testing with tolerance <0.1 was taken as one of the checks of having a good numerical simulation. Secondly, a good conditioning of the system algebraic equations yielded a singularity ratio (conditioning number of the global stiffness matrix), to remain within the satisfactory interval throughout the simulation [23].

4. Experimental determination of strain distribution

In order to homogenize the microstructure of the commercially pure aluminium, prepared Rastagaev probes were heat treated for 16 h at 600 °C. Air cooling resulted in uniform grain sizes with mean linear intercept $d = 0.25$ mm [24]. Twelve previously prepared Al99.5 billets were accordingly upsetted to have logarithmic strain from 0.1 to 0.12 in steps of 0.1. After upsetting all the probes were heat treated at 500 °C for 1 h and then horizontally cut. Prior to metallographic examination section surface was prepared by: wet grinding, polishing and anodic oxidation in 40% HBF_4 solution in distilled water. Crystal structure of the prepared surface was photographed under polarized light, and mean linear intercept correlated to the strain of each probe. This resulted in calibration curve shown in Fig. 3.

Al 99.5 billet was equivalently heat treated before and gear after the cold forging and then horizontally cut at intersecting plane 8 mm from the gear basis. The section surface was prepared in the same manner as for the probes and mean linear intercept determined. Comparison of the grain sizes via calibration curve resulted in experimentally estimated strain determination shown in Fig. 4.

5. Comparison of the experiment and simulation

Experimental determination of the strain distribution was performed along the numerically obtained contour bands shown in Fig. 4. It was necessary to use this kind of approach since MLI method gives large quantities of data that were easiest to handle in this manner.

Both simulation and experiment give similar strain distributions bands. Since there are no grain sizes corresponding to 0.1 strain and numerically obtained equivalent strain $\varepsilon_{\mathrm{eq}}^{p}$ (2) is greater than 0.2, calibration curve gives unique, functional relation between grain sizes and estimated strain. This results in comparison of estimated and equivalent strain given in Fig. 4.

$$\varepsilon_{\mathrm{eq}}^{p} = \int \dot{\varepsilon}_{\mathrm{eq}}^{p}\,\mathrm{d}t = \int \left(\frac{2}{3}\dot{\varepsilon}_{ij}^{p}\dot{\varepsilon}_{ij}^{p}\right)^{1/2}\mathrm{d}t \tag{2}$$

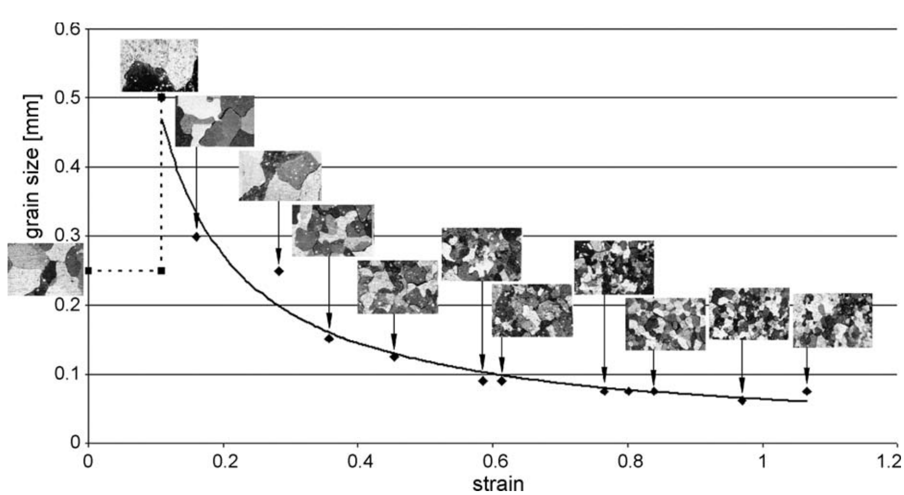

Fig. 3. Calibration curve.

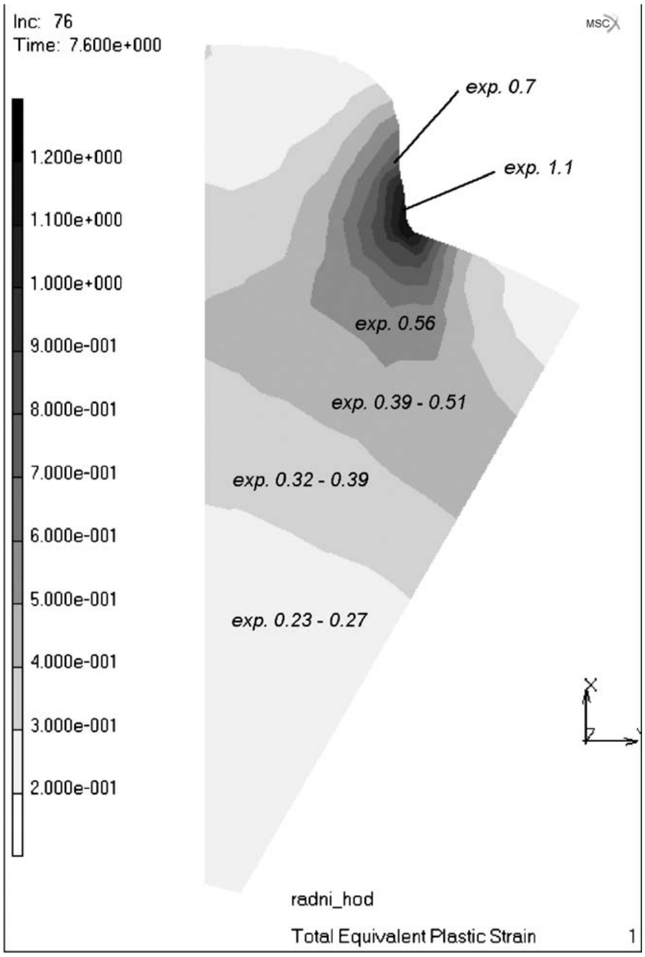

Fig. 4. Strain distribution obtained by numerical simulation and experimentally by the use of calibration curve (denoted with exp.).

For the $\varepsilon_{\text{eq}}^{p} = 0.2 - 0.5$, estimated strain has a maximal absolute error of ±0.03. This can be attributed to both experimental and numerical errors. Contour bands with a larger $\varepsilon_{\text{eq}}^{p} > 0.5$ represent less than 1/10 of the section area. Therefore, an average strain estimation was made as shown in Fig. 4. Interesting fact is that the simulation has given a direction for the precise examination of the tooth base. Extremely small grains around the sharp corner yield $\varepsilon > 0.7$. Moreover, surface grains exhibit even larger deformations that need more precise experimental and numerical examination.

Force–stroke diagram given in Fig. 5 for the model with friction, performs a numerically explainable behaviour. In the beginning, sudden load rise comes from step movement of the punch and its sudden contact with upper side of the billet. Second load rise takes place after punch has travelled a distance of 0.5 mm and billet comes in contact with the surrounding die.

Remeshes at stroke $s = 1.9$, 2.6, 3.1 and 3.8 mm result in punch force jumps as it can be seen from Fig. 5. Model without friction gives a steep load rise in the end of simulation coming from a die corner filling. Experimental rise of the force is more gradual, since the elasticity of tooling and the press itself compensates the corner filling load rise.

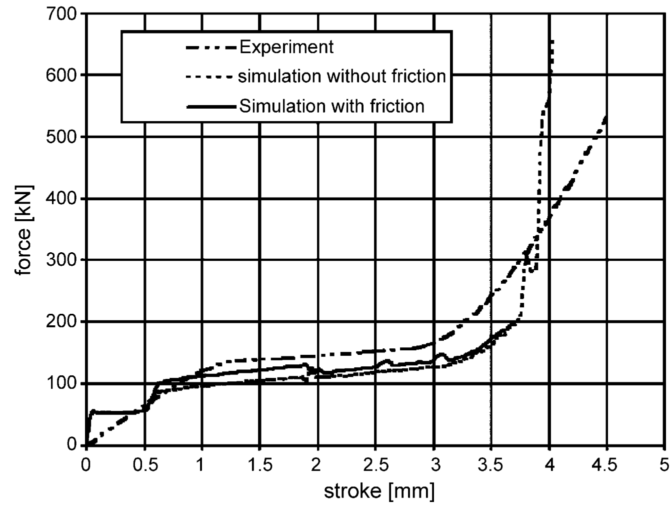

Fig. 5. Comparison of force–stroke diagrams.

6. Conclusion

Commercial program packages, offering the possibility of FE analysis undergo a constant improvement. Their complexity coming from the combination of the numerical mathematics, computer technology and particular field of continuum mechanics results in loss of robustness particularly when large meshes are in question.

Cold forging technology is a highly specific area of the research and production. Therefore, it is possible and necessary to apply the FE program packages in its development. Improvement of the model by the means of reverse engineering is the only way to make use of commercial multi-purpose non-linear programs like MSC.Marc Mentat 2005r2. Moreover, due to its phenomenological background friction can be modelled only by the use of reverse engineering.

Complete overlapping of the force–stroke diagram can be obtained by changing the value of friction coefficient. The only question that arises in that case is stability. Particular friction model can result in premature termination of simulation, excessive prolongation of calculation time or yield erroneous results. Therefore the FE method, besides the well-known theory usually requires a trial and effort to obtain a correct numerical model.

References

[1] B.I. Tomov, V.I. Gagov, Modelling and description of the near-net-shape forging of cylindrical spur gears, J. Mater. Process. Technol. 92–93 (1999) 444–449.

[2] O. Eyercioglu, Developments and performance analyses of precision forged spur gears, Ph.D. Thesis, University of Birmingham, 1995.

[3] M.L. Alves, J.M.C. Rodrigues, P.A.F. Martins, Cold forging of gears: experimental and theoretical investigation, Finite Elem. Anal. Des. 37 (2001) 549–558.

[4] N.R. Chitkara, M.A. Bhutta, Computer simulation to predict stresses, working pressures and deformation modes in incremental forging of spur gear forms, Int. J. Mech. Sci. 38 (1996) 871.

[5] N.R. Chitkara, M.A. Bhutta, Near-net shape forging of spur gear forms: an analysis and some experiments, Int. J. Mech. Sci. 38 (1996) 891.

[6] J.C. Choi, Y. Choi, K.D. Hur, C.H. Kim, A study on the forging of spur gears, Int. J. Mech. Sci. 38 (1996) 1333.

[7] J.C. Choi, Y. Choi, Precision forging of spur gears with inside relief, Int. J. Mach. Tools Manuf. 39 (1999) 1575.
[8] D.Y. Yang, N.K. Lee, J.H. Yoon, J.L. Chenot, N. Soyris, A three-dimensional rigid-plastic finite element analysis of spur gear forging using the modular remeshing technique, Process. Inst. Mech. Eng., Part B, J. Eng. Manuf. 205 (B2) (1991) 111.
[9] M. Fu, B. Shang, Stress analysis of the precision forging die for a bevel gear and its optimal design using the boundary-element method, J. Mater. Process. Technol. 53 (1995) 511–520.
[10] J.H. Yoon, D.Y. Yang, A three-dimensional rigid-plastic finite element analysis of bevel gear forging by using a remeshing technique, Int. J. Mech. Sci. 32 (1990) 277.
[11] T. Birker, T. Pedersen, Studies of contact problems and cyclic plasticity in high-pressure tools by use of non-linear FE analyses, in: Proceeding of the Eighth ANSYS Conference, vol. 1, Pittsburgh, USA, 1998, pp. 101–110.
[12] J. Groenbaek, T. Birker, Innovations in cold forging die design, J. Mater. Process. Technol. 98 (2000) 155–161.
[13] S. Samanta, Helical gears: a novel method of manufacturing, in: IT Proceedings of NAMRC-IV, Batelle Columbus Laboratories, Columbus, OH, USA, 1976, pp. 199–205.
[14] Y.B. Park, D.Y. Yang, Finite element analysis for precision cold forging of helical gear using recurrent boundary conditions, Proc. Instn Mech. Engrs, Part B, J. Eng. Manuf. (1997) 231–240.
[15] V. Szentmihali, K. Lange, Y. Tronel, J.L. Chenot, R. Ducloux, 3-D finite element simulation of the coldforging of helical gears, J. Mater. Process. Technol. 43 (1984) 279.
[16] V. Vazquez, K. Sweeney, D. Wallace, C. Wol, M. Ober, T. Altan, Tooling and process design to cold forge a cross groove inner race for a constant velocity joint physical modelling and fem process simulation, J. Mater. Process. Technol. 59 (1996) 144.
[17] V. Vazquez, T. Altan, New concepts in die design–physical and computer modeling applications, J. Mater. Process. Technol. 98 (2000) 212–223.
[18] M. Ober, K. Sweeney, M. Knoerr, M. Altan, Design of a Tooling for Cold Forging a Cross Groove Inner Race, Report No. ERC/NSM-B-94-30, The Engineering Research Center for Net Shape Manufacturing, The Ohio State University, Columbus, OH, 1994.
[19] H.J. Haepp, K. Roll, Mathematical modelling of metal forming processes in automotive industry, in: Advanced Technology of Plasticity, Proceedings of the 6th ICTP, vol. I, September 19–24, 1999.
[20] M. Plancak, D. Vilotic, P. Skakun, A study of radial gear extrusion, Int. J. Forming Process. 6 (1) (2003).
[21] E. Doege, H. Meyer-Nolkemper, I. Saeed, Fliesskurvenatlas metallischer Werkstoffe, Carl Hanser Verlag Muenchen Wien, 1986, ISBN 3-446-14427-7.
[22] N.V. Hattangady, Coarsening of mesh models for representation of rigid objects in finite element analysis, Int. J. Numer. Meth. Eng. 44 (1999) 313–326.
[23] MSC. Software Corporation, MSC. Marc Volume A – Theory and User Information, Santa Ana, California, 2005.
[24] F. Schucker, in: R.T. De Hoffand, F.N. Rhines (Eds.), Quantitive Metallography, McGraw-Hill, New York, 1968 (Chapter 7).