NUMERICAL SIMULATION OF CYCLIC EXTRUSION PROCESS FOR ALUMINUM ALLOY A6060

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In the research reported in this paper, numerical simulations are conducted to analyze the process of cyclic extrusion. The finite element analysis (FEA) simulation was carried out using Forge 2009- FEA software, specifically produced for metal forming simulation. An axis-symmetrical 3D geometric model of tools and billet was constructed for the analysis. The simulation results confirm the suitability of the current finite element software for modeling the three-dimensional cyclic extrusion of aluminum billets.

Keywords: aluminum alloy, FEA simulation, Forge 2009, cyclic extrusion.

1. Introduction

Cyclic extrusion (CE) is one of the methods of applying severe plastic deformation (SPD) to polycrystalline materials in order to refine the grain size up to the sub-micrometer or nanometer level and, in consequence, to obtain extreme mechanical properties of the material. Other widely applied SPD methods include equal-channel angular pressing (ECAP), high-pressure torsion (HPT), accumulative roll bonding (ARB), multi-axis compression, and others. Unlike traditional cold rolling or drawing processes of large plastic deformation, the SPD techniques that employ cyclic strain paths lead to an essentially unchanged shape of the specimen after processing [1]. Cyclic extrusion (CE) as the method of applying severe plastic deformation originated in 1979 [1]. The investigations started using a laboratory version of the CE equipment. A schematic illustration of the cyclic extrusion compression (CEC) process is shown in Fig.1. During plastic flow between two chambers of diameter d_o through the connecting channel of diameter d_m, compression occurs simultaneously with extrusion, so that the sample is restored to its initial shape.

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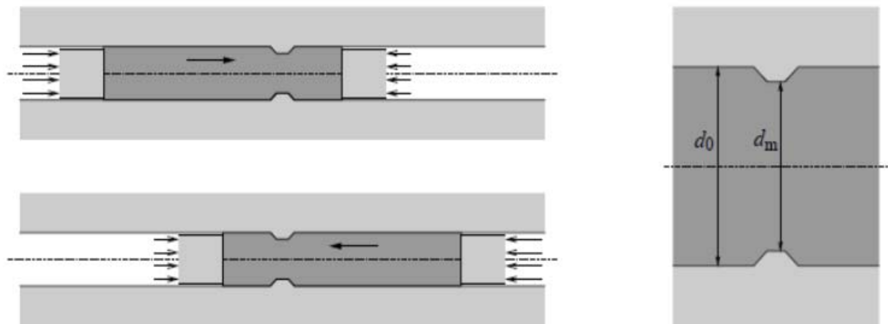

Fig. 1. Schematic illustration of the cyclic extrusion compression process [1].

Finite element analysis (FEA) has been developed during the last decades as a very useful tool for analysis of metal forming processes [2,3,4]. Recent progress in FEA, together with increasingly powerful computers, has permitted increased use of such numerical modeling. Hence, today it is possible to FEM-simulate the metal forming processes at various design stages.

The extrusion pressure requirement and the maximum of the extrude temperature depend on the alloy and its metallurgical conditions, billet length, billet temperature, reduction radio, die design and its conditions, etc. [5].

A finite element analysis (FEA) of the cold cyclic extrusion of high-grade (AA1100) aluminum process was undertaken in parallel with the experimental program. Data obtained from the FE model included die-work piece contact pressure, effective stress and strain and material deformation velocity [6].

The simulations of aluminum A6060 cyclic extrusion under various conditions, investigates the stress–strain distribution, the damage factor distributions, the die load and the flow velocity of the billet at the exit. The relative influences of the semi-angle of the die, the extrusion ratio and the friction factors are systematically examined [7]. The present study employs FORGE 2009 finite element code to predict the temperature evolution throughout the whole cycle of extruding an A6060 billet.

2. Theoretical aspects

FEM simulation of metal forming is highly complex and computation intensive. This is due to extreme nonlinearities because of large strains, plastic flow of anisotropic materials, with interfacial friction between irregular-shaped surfaces under changing contact. Because of this, it is difficult to obtain analytical correlations to such problems for quantitative evaluation of temperature, stress, and strain distributions, within the deforming body. It is therefore common to use the FEM for this purpose.

One of the most important elements for a computer simulation of plastic deformation processes is the model of deformed materials, usually describing the flow stress as a function of the deformation conditions. The accuracy of this material model depends on both the mathematical structure of the model and the proper experimental determination of the material parameters used in the model.

Constitutive equations are used to describe the changes in strength observed to occur in materials being deformed. Such equations are used to predict forces, distortions, stresses, etc. that can be encountered during mechanical processing of materials. The general form of constitutive equation is:

$$\overline{\sigma} = f(\varepsilon, \dot{\varepsilon}, T, \sigma^{*}) \tag{1}$$

where: σ - true stress; ε - true plastic strain; $\dot{\varepsilon}$ - strain rate; T- temperature; σ^{*} - parameter dependent of the history of deformation.

Empirical and semi-empirical relations obtained from experimental data are widely used in deformation models because they are easier to develop. The most widely used constitutive equations for the analysis, the simulation and the design processes of metal forming at ambient temperature and at relatively low rates of deformation, are:

- Hollomon equation: $\sigma = C\varepsilon^{n}$ (2)
- Ludwik equation: $\sigma = \sigma_0 + C\varepsilon^{n}$ (3)
- Swift equation: $\sigma = C(\varepsilon + \varepsilon_0)^{n}$ (4)
- Voce equation: $\sigma = \sigma_s - (\sigma_s - \sigma_0)\exp(-n\varepsilon)$ (5)

None of the above equations are entirely satisfactory for all materials and deformation conditions. These simple equations can be used for a satisfactory description of the stress-strain behavior of particular materials such as steels, copper and aluminum alloys.

In the case of hot working processes for large strain, the effect of strain on flow stress can be neglected. There is a particular relationship among flow stress, strain rate, and deformation temperature. The combined effects of temperature and strain rate on the deformation behaviors can be expressed by the Zener–Hollomon parameter [9].

$$\sigma = f(\dot{\varepsilon}\exp\frac{Q}{RT}) = f(Z) \tag{6}$$

$$Z = \dot{\varepsilon}\exp\frac{Q}{RT}$$

In the above relations the parameters have the following signification:

σ_0 - the yield point; σ - the flow stress; σ_s, n, - the coefficients of strain hardening; ε_0 - pre-strain; Q - activation energy for deformation (kJ/mol); R - the universal gas constant 8.314 J/(mol·K); Z - Zener-Hollomon parameter.

The techniques for cyclic extrusion of different materials are dependent, to a large extent, on the extrusion temperature. The essence of cold working is to reduce the yield stress and thus increase extrusion speed for a given press load. Critical parameters for successful and economical cold extrusion include the method of billet preparation, the amount of pressure and rate of speed used for extruding and the type of lubricant employed [6].

3. Simulation process

Aluminum alloy A6060 is one of the most used high-strength material for aircraft structural components. The alloy has a very small extrusion window, as restrained by its high flow stress and by its low incipient melting point. In order to determine the flow curve for A6060 aluminum alloy, torsion tests were carried out, using samples of 10 mm in diameter and 30 mm in length. Test was carried out at stain rates of 0.2 [s^{-1}].

A simulation of the cyclic extrusion process was performed using the finite element software. This was achieved by constructing an accurate three dimensional CAD model of the process. The model was meshed with appropriate elements and material properties and boundary conditions were added. The geometries of the billet, die, container and stem were generated in SolidWorks and the meshes within their space domains in FORGE 2009 [9].

The physical properties of the aluminum alloy used in the computer simulation are given in Table 1. The billet was considered thermo-viscoplastic whiles the tools deformable, and both of these material models neglected the elastic deformation. The friction factor, according to Tresca friction law, at the billet–punch and billet–die interfaces were assumed to be 0.2. The correlation of flow stress with strain as a function of temperature and strain-rate included in the FORGE software package was utilized [9].

Table 1.

Physical properties of aluminum alloy A6060

Property	A6060
Density [kg/m^3]	2800
Heat capacity [J/K]	2,45
Thermal conductivity [W/(m·K)]	250
Emissivity	0,15

The process parameters used in the simulations are given in Table 2.

Table 2.

Process parameters used in simulations

Billet height [mm]	30
Billet diameter [mm]	10
Die semi angle γ [^{0}]	30
Extrusion ratio	2.77
Billet temperature [^{0}C]	20
Container and die temperature [^{0}C]	20
Ram speed [mm/s]	10
Friction factor at the work piece–die interface	0.2
Mesh number of the billet	9761
Mesh number of the die	18342

4. Simulation results

Figure 2 shows the parts discretization respectively for billet and extrusion tools. The temperature distribution in material is a combined effect of the following thermal processes: heat generation due to deformation; heat generation due to friction and shear at the billet–container/stem/die face interfaces; heat generation due to friction at the extrude–die interface; heat loss from the tooling and extrude to the ambient surrounding; heat conduction within the work piece (billet and extrude) [5].

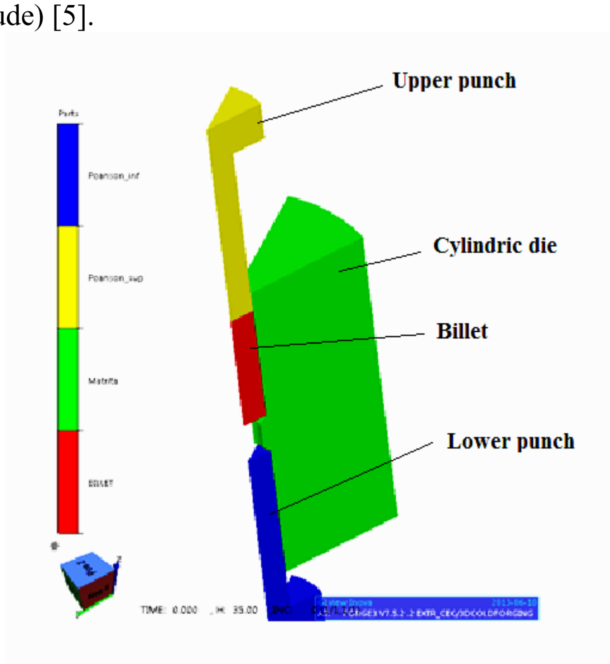

Fig. 2. Parts discretisation

Homogeneity of strains and the quantity of the deformed samples global deformation response induced by cyclic extrusion were taken from the actual distribution of deformations in process simulation made using FORGE 2009.

We simulated 14 passages for each type of stencil (with Ø5.5 mm crossing area) with thrust force of 20 kN constant.

We used a slice of 36^o from the billet–container-punches in terms of axial symmetry and less time analysis-approx. 6 hours per shift (Fig. 2). Both the outer wall surface and the inside of the channel matrix were deemed to be rigid and stationary conditions limit the motion axes OX and OY is a zero. Inspecting was considered rigid, with a move away in the vertical plane with a speed of v = 10 mm/s, similar to the values used for experimental tests.

Nonuniform deformations with differences of higher values are observed, both near the entrance and the exit of the die (the shift from the Ø10 to Ø5.5 mm) the value of deformations are as follows:

- between 1.1 to 11 for first pass;
- between 1.8 to 18 for second pass;
- between 2.5. to 25 for third pass;
- between3.2 to 32 for fourth pass;
- between 5 to50 for 8^{th} pass;
- between 6,8 to 68 for 12^{th} pass;
- between 7.8 to 78 for 14^{th} pass.

These thermal events inside the deforming material are not experimentally obtainable. The overall temperature of the billet affects the flow stress of the billet material and its variation should be visible from the extrusion pressure. Some of these examples are represented in (Fig. 3-5).

During the simulation, were traced the evolution of the 10 nodes of type tetrahedron elements to achieve the effect of some parameters on the deformation behavior, distribution of strains and force necessary to cyclic extrusion process. Describing the behavior to deformations, associated with the movement of each node, forming areas of distorted network, to areas where the metal detaches from the wall matrix, provides information on the size of the computed deformations in any node and at any stage of the process.

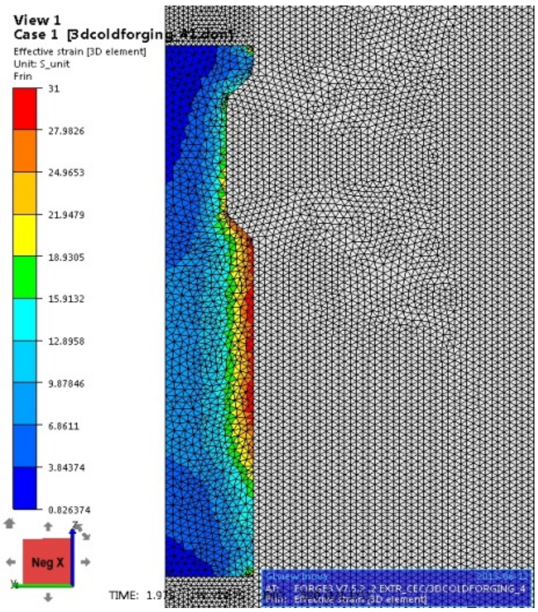

Fig. 3. Temperature distribution after the third pass of deformation.

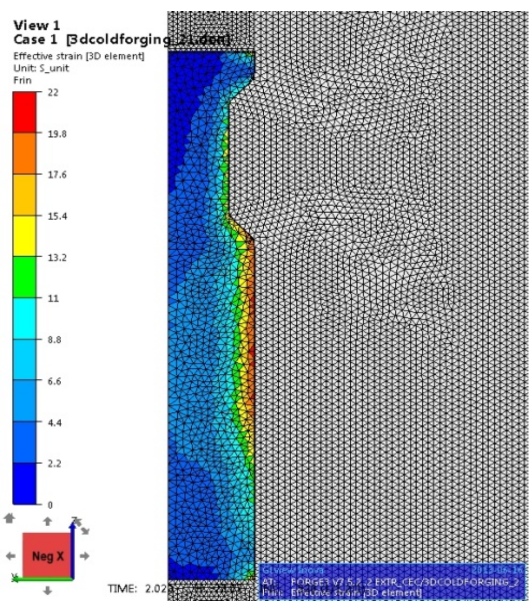

Fig. 4. Temperature distribution after the fifth pass of deformation.

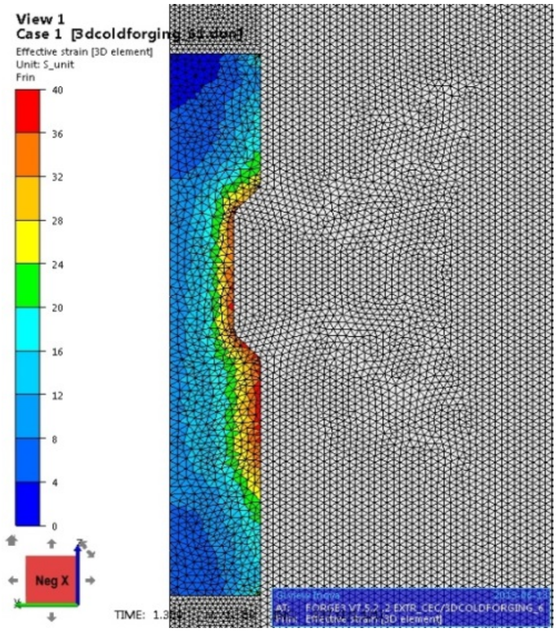

Fig. 5. Temperature distribution after the seventh pass of deformation.

5. Conclusions

This study has utilized three-dimensional finite element code to examine the plastic deformation behavior of an aluminum billet during its symmetric cyclic extrusion through a double conical die. The simulation results are in agreement to theoretical and experimental aspects regarding to cyclic extrusion.

In the cyclic extrusion process, initial billet temperature, friction factor and extrusion speed are the main parameters that affect the evolution of the plastic deformation process. The temperature distribution of billet is complicated and it can be calculated only by numerical methods, respectively by finite element method.

The temperature of the billet affects the flow stress of the billet material and its variation should be visible from the extrusion pressure. In Fig. 3-5 are shown the increase of temperatures in the cylindrical die after a number of three, five and seven passes respectively of the deformation cyclic flows. Also, it can be seen the distribution of pressure inside the billet in the three-dimensional finite element codes.

Changes of temperatures between dies and billets are influenced in a great manner by the lubricating process and implicit due to friction between extrude and die. It can be note that the deformation speed, which is a main factor involved in process is considered to be a constant at value of 10 mm/s.

Comparison of the temperature distributions at different stages of the process, demonstrates the non-stationary characteristics of thermal effects within the billet.

REFERENCES

[1]. *J. Richert, M. Richert,* "A new method for unlimited deformation of metals and alloys", in Aluminum, **vol. 62**, no. 8, 1986, pp. 604–607;

[2]. *J.L. Chenot, E. Massoni*, „Finite element modelling and control of new metal forming processes", in International J. Machine Tools & Manufacture, **vol. 46**, no. 11, 2006, pp. 1194–1200;

[3]. *P. Hartley, I. Pillinger*, „Numerical simulation of the forging process", in Comput. Methods Appl. Mech. Eng. **vol. 195,** 2006, pp. 6676–6690;

[4]. *N. Fietier , Y. Krahenbuhl, M. Vialard*, "New methods for the fast simulations of the extrusion process of hot metals", in J. Mater. Process. Technol; vol. **209**, Issue 5, 2009, pp. 2244–2259;

[5]. *L. Li, J. Zhou, J. Duszczyk*, "Prediction of temperature evolution during the extrusion of 7075 aluminum alloy at various ram speeds by means of 3D FEM simulation", in J. Mater. Process. Technol. **vol. 145,** no. 3, 2004, pp. 360–370;

[6]. *P. Tiernan, M.T. Hillery, B. Draganescu, M. Gheorghe*, "Modelling of cold extrusion with experimental verification", in J. Mater. Process. Technol. **vol. 168,** no. 2, 2005, pp. 360–366;

[7]. *C. Dyi-Chengn, S. Sheng-Kai, W. Cing-Hong, L. Sin-Kai,* "Investigation into cold extrusion of aluminum billets using three-dimensional finite element method", in J. Mater. Process.Technol. **vol. 192–193**, 2007, pp. 188–193;

[8]. *L. Ming-Song Chen, J. Zhong*, "Constitutive modeling for elevated temperature flow behavior of 42CrMo steel", in Computational Materials Science **vol. 42,** no. 3, 2008, pp. 470–477;

[9]. *Mariana Pop, D. Frunză, Adriana Neag,* „Application of numerical simulation in metal forming processes”, in Metalurgia **vol. 65**, no. 3, 2013, pp. 14-23.