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Three dimensional finite element study on torsion extrusion processing of 1050 aluminum alloy

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Abstract: The capability of the torsion extrusion (TE) process as a severe plastic deformation (SPD) method was compared with the conventional forward extrusion (FE) process. The TE and FE processes were successfully performed on AA1050 alloy samples at room temperature. To simulate the above mentioned processes, finite element analysis was carried out using the commercial elasto-plastic finite element analysis ABAQUS/Explicit Simulation. It is shown that load requirement for the TE process is lower than that for the FE process. The equivalent plastic strain calculated by the FEA proved that higher values of strain are imposed to the sample in the TE process. The strain distribution for the TE sample at the final stage of extrusion shows smoother strain gradient in comparison with the one produced by the FE process.

Key words: AA-1050 alloy; severe plastic deformation (SPD); torsion extrusion (TE); equivalent plastic strain; strain distribution; deformation energy

1 Introduction

Extrusion, though one of the most important manufacturing processes today, is a relatively heavy process in metalworking methods from the pressure requirement viewpoint [1]. In forward extrusion (FE), which can be used for manufacturing of special sections and hollow articles, the material is generally made to flow in the cold condition by application of a moderately high pressure. The applied pressure pushes the material through a cavity enclosed between a punch and a die. The extrusion process produces compressive and shear forces in the stock but no tensile force is created. This stress state makes it possible to have large deformation without tearing during the forming process.

The need for performing a similar process which maintains all advantages of the FE process but also reveals some improved product properties has always been traced [2]. A good candidate for replacing the FE process can be torsion extrusion (TE) process as one of the severe plastic deformation (SPD) methods. Unlike the FE process, the die in the TE process is not stationary, but it is rotating with a desired angular velocity to impose intensive shear strains to the final products [2]. Both processes can apply either high or low values of reduction in area on the specimen prior to entering the reduced section of the die.

The TE process was experimentally examined by some researchers for different materials. To begin with, CHINO et al [3] carried out the TE process on a commercial magnesium alloy. It was shown that an AZ31 alloy processed by the TE process exhibits a significant enhancement in ductility at room temperature. In addition, MA et al [4] performed the above process on a commercially pure lead. It was concluded that the extrusion load is reduced with die rotation and larger strains can be applied by increasing the die twisting speed although there is always some circumferential slippage between the specimen and the die. However, there is no detailed research on the modeling of the torsion extrusion process by the finite elements analysis.

Analyses of metal forming processes are commonly performed utilizing analytical, numerical, or physical techniques. Due to complexity of the equations involved in the analytical approach, the application of such methods is only practical for the case of simple geometry and boundary conditions [5]. The advancements in

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computer technology make significant contributions towards the application of numerical methods such as the finite element method (FEM) for solving incremental plasticity equations. Similar to the analytical methods, numerical techniques can also be used to predict the required forming load, tool/ work piece interface stress distribution, as well as some other information such as stress and strain distribution, tooling stresses or distortions, and temperature gradient for hot forming processes.

A number of experimental, analytical and numerical investigations of the continuous forward extrusion process have been reported by many researchers [6]. However, as a method which is comparable and in a few cases superior to the forward extrusion process, no report can be found on analytical or numerical simulation of the torsion extrusion process. The main aim of the present work is to study the differences between torsion and forward extrusion processes from load requirement, strain distribution and final product properties points of view. Thus, finite element analysis and experimental studies of both processes were performed simultaneously.

To carry out the FEA part of this study, a commercial elasto-plastic finite element analysis program ABAQUS/Explicit Simulation was employed to evaluate the plastic deformation behavior of the material during TE and FE processes as well as load and strain conditions met in these processes.

2 Experimental

Billets of 20 mm in diameter with a length of 40 mm machined out of AA1050 alloy, annealed at 550 °C for 2 h, and furnace cooled at rate of 25 °C/h, were used as raw materials. To carry out torsion extrusion process, an especial die-setup was designed and prepared. Sufficiently large length of contact must be created between the die and the work piece, since the frictional stresses are critical in a torsion extrusion process. Thus, a die with two extrusion stages was designed and also no lubrication was performed in order to make sure that the material is properly twisted in the rotating die. The diameter of the container was 20 mm and the diameters after the first and second stages of extrusion were 16 and 13 mm, respectively, which led to a total of 57% reduction in area. The rotating billet in the TE process was subjected to a 0.21 rad/s angular velocity and a 0.2 mm/s ram speed at ambient temperature. The FE process was also performed in the same die and with the same friction condition and ram speed while the angular velocity was zero.

3 Finite element analysis procedure

As it was mentioned in the previous section, the plastic deformation behavior of the specimens during the TE and FE processes were studied using the commercial elasto-plastic finite element analysis program ABAQUS/ Explicit Simulation [7]. The simulations were performed by 3D models in which the geometrical dimensions and mechanical properties of the specimens were exactly the same as those of the experimental samples.

In order to determine the deformation behavior of the materials used in the TE and FE processes, compression tests were carried out on the AA1050 samples at a constant crosshead speed of 0.2 mm/s up to a strain of 0.8. The obtained (σ—ε) data were then directly used in the FEA program. By curve fitting of the graphs obtained from the compression tests, the Ludwik's equation was calculated to be σ=124.3$\varepsilon^{0.318}$. The flow stresses corresponding to values of strain higher than 0.8, required for the simulation program, were obtained by extrapolation using the above equation.

The lubrication condition used in the experimental procedure led to a friction factor of m=0.18 at the die sample interface which was determined from a barrel compression test [8]. Then, in order to apply this value in the simulation, it was converted to the friction coefficient by using the following relation [9]:

$$\mu = \frac{m}{\sqrt{27(1-m^2)}} \tag{1}$$

which resulted in μ=0.035.

Eight-node linear brick elements (C3D8R) and 4-node 3-D bilinear rigid quadrilateral elements (R3D4) were used to mesh the billet and the rigid parts, respectively [7]. By varying the number of elements, it was found that 40000 elements would be sufficient for the initial deformable billet to study the local deformation of this strain rate insensitive material. The initial meshed sample is illustrated in Fig. 1.

As the meshed model became highly distorted during the simulation, adaptive meshing facility was necessary to analyze the applied large deformations and strains. This option of the software improves the elements shapes and aspect ratios during the plastic deformation by eliminating distortions caused by large strains and flow localization. The frequency and number of remeshing sweeps per increment applied for adaptive meshing were 1 and 10, respectively. The running time of the simulation was about 40 h on an Intel Pentium IV core 2 Duo PC.

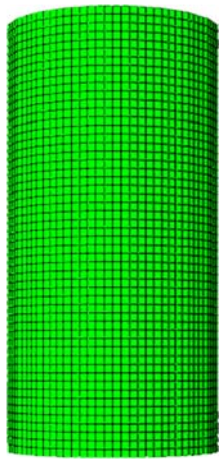

Fig. 1 Initial meshing of billet for FEA study

4 Results and discussion

4.1 Load requirement comparison

Figure 2 shows the experimental load—displacement graphs for the TE and FE processes. As can be observed, the TE process required lower load than the FE process. MA et al [4] introduced two mechanisms to explain the load reduction phenomenon in the TE process. 1) Die rotation causes the interfacial frictional stress to deviate from its original direction. This results in the reduction of the inactive friction stress (assuming a constant friction stress distributed over the die/material interface). 2) The internal shear stress in the circumferential direction changes the stress state within the material thus decreasing the primary stress according to the yield criteria.

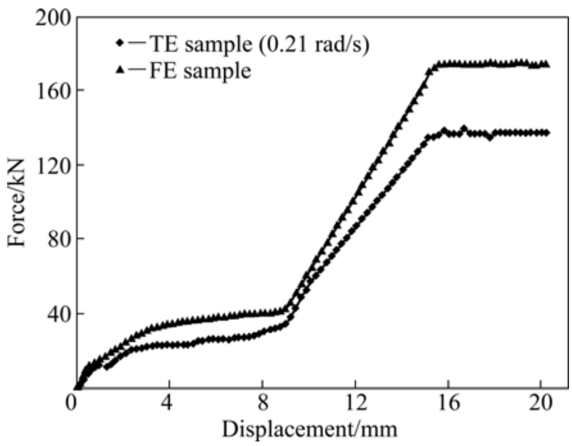

Fig. 2 Load—displacement curves of TE and FE processes obtained by experiments

However, it is important to mention that these two mechanisms will act only if sufficiently large frictional stresses are generated due to a moderate coefficient of friction. In other words, load reduction will not occur effectively if the material is not twisted with the same angular velocity as that of the die. The results of the simulations carried out at a constant friction condition showed that with increasing the angular velocity, a decreasing trend in the required load would not be observed for the whole range of angular velocity. In fact, for each coefficient of friction, with constant die geometry, a critical angular velocity exists up to which the billet and the die twist with the same velocity. At angular velocities higher than this critical value, slippage occurs at the die/billet interface. In this study, a proposed angular velocity of 0.21 rad/s was chosen for the experiments. To have more consistency, the same value was also chosen for the simulations.

4.2 FEA results

4.2.1 FEA verification

To verify the FEA results obtained in modeling of the TE process, the experimental and simulation load—displacement curves have been presented in Fig. 3. Good agreement can be noticed between the experimental and simulation results. By this comparison, it can also be concluded that the conditions selected in the simulations such as die angular velocity, punch speed and friction conditions are in good consistency with those in the experiments.

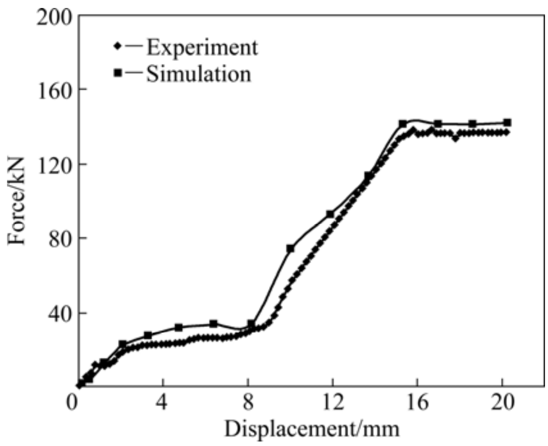

Fig. 3 Comparison of load—displacement curves obtained by experiment and simulation for TE process

Figure 4 shows the internal and kinetic energy of the simulated TE process. The internal energy is defined as the required energy for plastic deformation of the material in the supposed process [7]. The kinetic energy is related to the energy required for accelerating the billet during the plastic deformation [7]. According to the deformation energy concepts, in order to establish a quasi static condition, the magnitude of kinetic energy must be 10% of the internal energy [7]. Considering the energy values presented in Fig. 4, it can be concluded that a quasi-static condition has been accomplished in our FEM studies. Since the forming process was carried

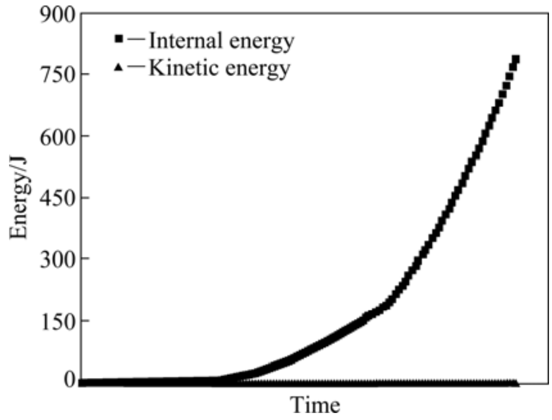

Fig. 4 Internal and kinetic energy of TE process obtained by simulation

out at the low speed of 0.2 mm/s, a quasi-static condition was also met in the experimental studies.

4.2.2 Energies comparison

It was observed in the previous section that the load requirement for the TE process is lower than that for the FE process. A same behavior is expected for the flow stress requirements in the above mentioned processes. However, the TE process imposes higher strain values compared to the FE process. Thus, it is expected to have rather similar $\sigma\times\varepsilon$ values for the two processes. As the internal energy is obtained by integration of the flow stress vs strain curve during plastic deformation, it is reasonable to have similar values of the internal energy for these two processes. Figure 5 clearly shows that there is no considerable difference in internal energy values of the TE and FE processes.

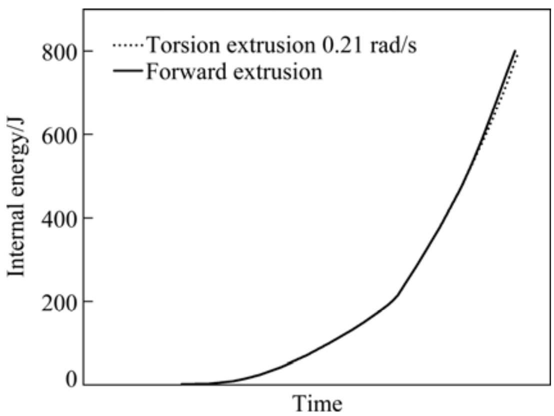

Fig. 5 Internal energy comparison for TE and FE processes obtained by simulation

The most remarkable energy difference is related to the friction energy. Figure 6 shows the variation of friction energy during the TE and FE processes. As can be seen, higher values of friction energy are generated in the TE process than in the FE process. This phenomenon can be justified by considering the friction surfaces in the TE process. In this process, the material courses more distances due to the angular motion of the die. Consequently, higher length of contact exists in the TE process, which leads to higher frictional stresses. The required energy for overcoming these frictional stresses was provided by an electrical motor, which can be considered an external work supplier. Therefore, although the required load for extruding the specimen in a TE process is lower than in the FE process, the overall energy requirement for the TE process is higher.

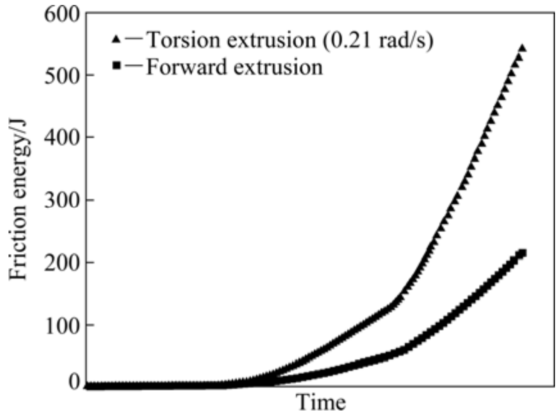

Fig. 6 Friction energy comparison for TE and FE processes obtained by simulation

4.2.3 Material flow

In the present study, the FEA was performed both with and without automatic adaptive meshing. During the plastic deformation, besides the shape change of the elements, their aspect ratios become larger continuously. Validity of the FEA results with such highly distorted element may be a big question. Therefore, improving the element shapes and aspect ratios is necessary. Thus, utilizing the automatic adaptive meshing tool seems inevitable. However, since automatic adaptive meshing causes the initial elements to maintain their shapes and aspect ratios, these elements would not be able to show the nature of the plastic deformation. Therefore, although load, energy and strain values were all calculated in the presence of automatic adaptive meshing, the FEA was also performed without this option to understand the nature of material flow in the TE process.

Figure 7 shows the surface elements of the material flowing in the TE process, which is obtained by performing FEA with and without automatic adaptive meshing. As can be seen, the material flow is not clearly distinguished in the presence of automatic adaptive meshing (Fig. 7(a)) because of element sweeping and remeshing. Instead, without automatic adaptive meshing, the elements exactly show the nature of plastic flow during the TE process (Fig. 7(b)). It can be observed that the elements change their vertical orientation and twist on the surface of the die during this process. The extent of element twisting on the surface of the die at a specific angular velocity is directly related to the level of frictional stresses at the die/billet interface.

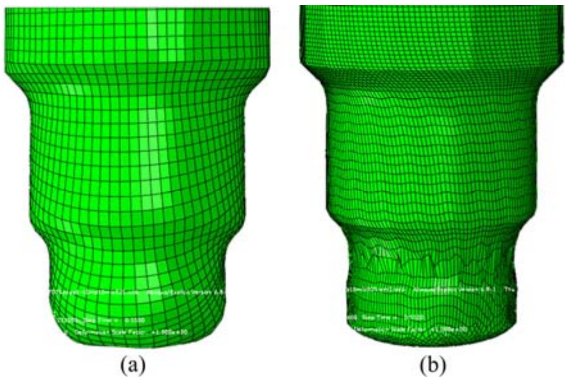

Fig. 7 Material flow in TE process: (a) With automatic adaptive meshing; (b) Without automatic adaptive meshing

4.2.4 Strain distribution

Equivalent plastic strain contours for a section normal to the extrusion direction in both the FE and TE processes at the final stage of extrusion are depicted in Fig. 8. It can be seen that higher values of strain were experienced by the surface which is directly in contact with the die walls. This phenomenon, commonly observed in the extrusion processes, is related to the higher frictional stresses at the die/billet interface. On the other hand, the elements at or near the centerline are not much affected by these frictional stresses.

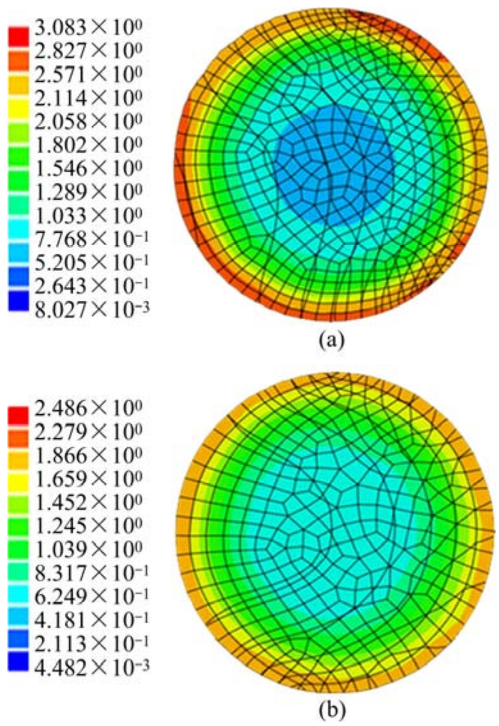

Fig. 8 Equivalent plastic strain contours at a cross section normal to extrusion direction in final stage of extrusion: (a) FE process; (b) TE process

In order to quantitatively survey the deformation gradient, the strain values were determined at nodes locating on a path through the final cross section of the extruded samples. Figure 9 shows the differences in strain distribution between the TE and FE processes. It is obvious that the values of strain are higher in the TE process. However, the most remarkable effect of die rotation in the TE process is the penetration of effective strain from the die/billet interface towards the centerline. This results in a smoother strain gradient in the TE sample and is ascribed to the higher shear stresses at the surface of a TE die.

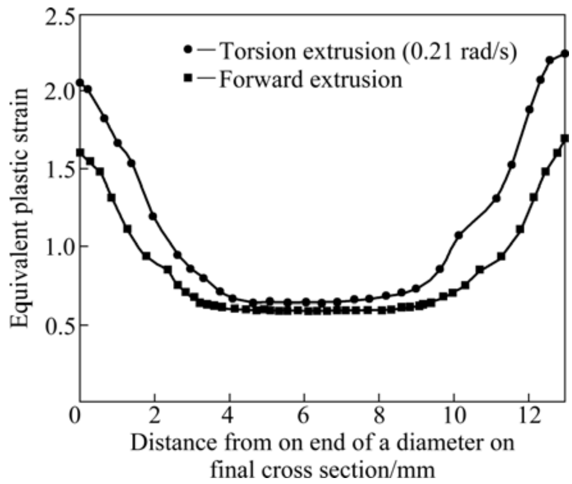

Fig. 9 Equivalent plastic strain distribution at a cross section normal to extrusion direction in final stage of extrusion

5 Conclusions

Loads required for performing the FE and TE processes were compared and the results showed lower load requirement for the TE process. However, the overall energy requirement for performing the TE process was higher than for the FE process. The finite element analysis was carried out using ABAQUS/ Explicit. The FEA prediction of the extrusion loads were in good agreement with the experimental values, which confirmed the validity of the FEA. By estimating the effective strain as well as the strain distributions through the samples, the FEA was also utilized for a better understanding of the deformation features in a TE process. The strain distribution comparison of the FE and TE samples showed smoother strain gradient in the TE samples, which can be considered as one of the most valuable advantages of the TE process over the FE process.

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1050 铝合金扭转挤压加工的 3D 有限元分析

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摘　要：研究了扭转挤压做为一种大塑性变形加工技术的可行性，并将其与普通的正挤压进行比较。在室温下对 AA1050 铝合金成功进行了扭转挤压和正挤压。采用商用有限元软件 ABAQUS/Explicit 模拟挤压过程。结果表明，在扭转挤压中，所需的载荷要比正挤压所需的小。有限元分析结果表明，在扭转挤压中，试样承受了较高的等效塑性应变，在挤压的最后阶段扭转挤压试样中的应变分布较之正挤压更为平滑，均匀。

关键词：AA1050 铝合金；大塑性变形；扭转挤压；等效塑性应变；应变分布；变形能

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