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Process simulation of friction extrusion of aluminum alloys

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Abstract. The friction extrusion (FE) process is a solid-state material processing technique in which a translating extrusion die is pressed against a billet/feedstock material in a rotating extrusion container to produce an extruded rod or wire. A key aspect of FE is the generation of severe plastic deformation and frictional heat due to the relative rotation, leading to an improved microstructure. Numerical simulations of FE are highly complex due to contact between the tool and the workpiece, and the interplay between thermo-mechanical conditions and the present severe plastic deformation. In the present work, a three-dimensional finite element model is developed to study the material flow behavior for different extrusion ratios for a 60° die angle during friction extrusion. The developed model is numerically validated against experimental data. The spatial temperature and strain distributions illustrate the effect of extrusion ratio on the deformation characteristics of the extruded aluminum alloys, thereby assisting in understanding the material flow behavior.

Introduction

Extrusion is a solid state forming process in which a metal feedstock is forced through an orifice or die opening in order to obtain a reduction in diameter and increase in length of the feedstock. In direct extrusion, the extruded metal is forced to flow in the direction of applied force, while in indirect extrusion, the metal flows in the opposite direction. The friction extrusion (FE) process is a relatively novel approach compared to conventional extrusion because of the added rotational motion. This process was developed and patented in 1993 by The Welding Institute, UK [1]. An illustration of the indirect FE setup and mechanism of operation are shown in Fig. 1.

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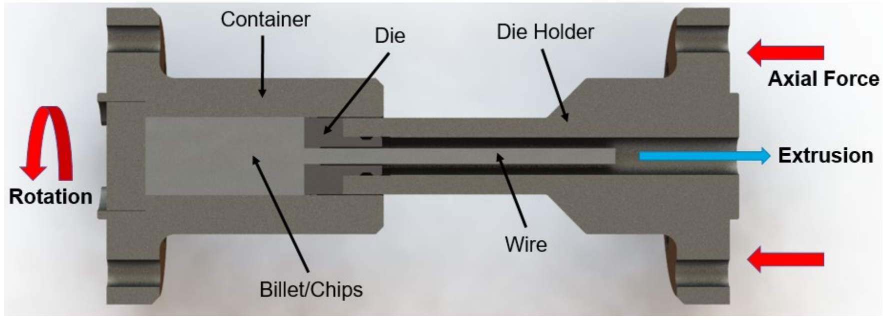

Fig. 1. Schematic of friction extrusion setup. The figure is reprinted from [2], under the terms of the Creative Commons Attribution 4.0 license (https://creativecommons.org/licenses/by/4.0).

FE involves relatively high pressure and relative rotation to force the metallic feedstock in the container through the die, resulting in a fully consolidated extrudate. As a result, reshaping billets into rods, tubes, and wires is possible through FE. Based on the process features, FE is capable of meeting the increasing demand of producing materials with improved mechanical properties [3] for application in automobile and aircraft industries. FE also provides a suitable alternative for material processing thus lower force and energy are required since more heat is generated via friction and rotation as compared to conventional extrusion where preheating the feedstock before extrusion is necessary in order to minimize the force required for extrusion.

The quality of the extrudate has been associated with a number of factors. In FE experiments, the extreme changes observed in processing characteristics and microstructural evolution have been attributed in particular to the friction condition [4], where the friction condition controls the introduced strain and thermal evolution [2,4]. For instance, Peng et al. [5] ascribed the formation of hot cracks during extrusion to the material flow governed by the temperature gradient across the wire diameter. Furthermore, the work from Yu et al. [6] showed that the die angle has a significant influence on the material flow, where the die surface geometry affects the frictional heating at the contact region. Therefore, it is of interest to study the influence of variable extrusion ratios on the material flow behavior.

A fundamental understanding of the mechanism of heat generation and related material flow during a friction-based process is of high significance because it can minimize the number of trials and therefore cost of experiments. Numerical models can help significantly in this regard, where a suitable description of the friction conditions is essential for processes like FE to achieve correct simulation predictions. Often, a constant friction value with a suitable friction law is used in numerical calculations, especially in friction-based processes performed using finite element method (FEM). The commonly adopted friction models in FEM are shear and Coulomb friction models. Shear friction models with constant friction factor have been applied in FE [7], friction stir welding (FSW) [8,9] and refill friction stir spot welding (refill FSSW) [10], whereas the Coulomb friction model is less frequently applied [11]. One example includes the application of a temperature-dependent friction coefficient in a simulation of refill FSSW [12]. Furthermore, to model the material response during thermo-mechanical processing, a constitutive model is also necessary, which accounts for the thermal and mechanical effects. One of the simplest models in this regard is the Arrhenius constitutive model, which is widely employed to describe the relationship between flow stress, strain rate and temperature at elevated temperatures in metallic materials [13].

In the present model, the effect of extrusion ratio on the process and thermo-mechanical conditions is studied. The process parameters used are deduced from a force-controlled FE experiment. The description of the experimental setup, the numerical method and the simulation inputs are presented in the following section.

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Experimental Setup and Finite Element Method

The FE process is performed on the FE100 (Bond Technologies, IN, USA), a dedicated friction extrusion machine. The tooling setup consists of a rotating 42CrMo4 steel container with charged AA2024 billet and an X40CrMoV5-1 die, featuring a 60° die angle and 10 mm die bore sizes as shown in Fig. 2(a). The experiment is conducted only for the 10 mm die bore with one billet, serving as validation data for the numerical simulation. The experiment is performed force-controlled, where a constant extrusion force of 300 kN and spindle rotation of 90 rpm are applied. The temperature was recorded via a K-type thermocouple at two-thirds of the die radius within the die, located 18 mm from the die face, as shown in Fig. 2(a). In experiment, the feedstock material in the as-cast condition is machined to have a based cylindrical shape of 50 mm length and 49.50 mm diameter, with a chamfer of 60° angle and 5 mm height at the edge, see also Fig. 3(a). The billet is locked against rotation towards the container. For initiating FE, a program step with higher rotation and lower force (300 rpm, 50 kN) is used to ensure defined contact between the die and feedstock to avoid torque overload.

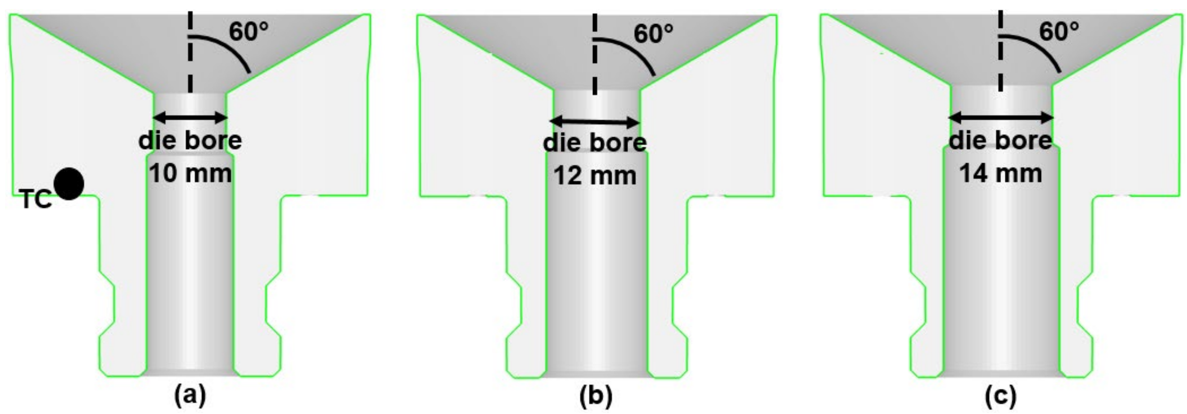

Fig. 2. Schematic extrusion die showing angle, including the location of the thermocouple (TC). Variable die bores are investigated, leading to different extrusion ratios: (a) ER = 25.0, (b) ER = 17.36, and (c) ER = 12.25.

The numerical model is set up in DEFORM 3D. The rotating extrusion container and the translating extrusion die, Fig. 3(b), are modeled as rigid and meshed with approximately 20,000 elements each to account for thermal conduction. The workpiece is modeled as rigid-viscoplastic material, where an adaptive mesh with approximately 50,000 elements with variable size is applied to resolve the thermo-mechanical properties at the contact region with the die as depicted in Fig. 3(c).

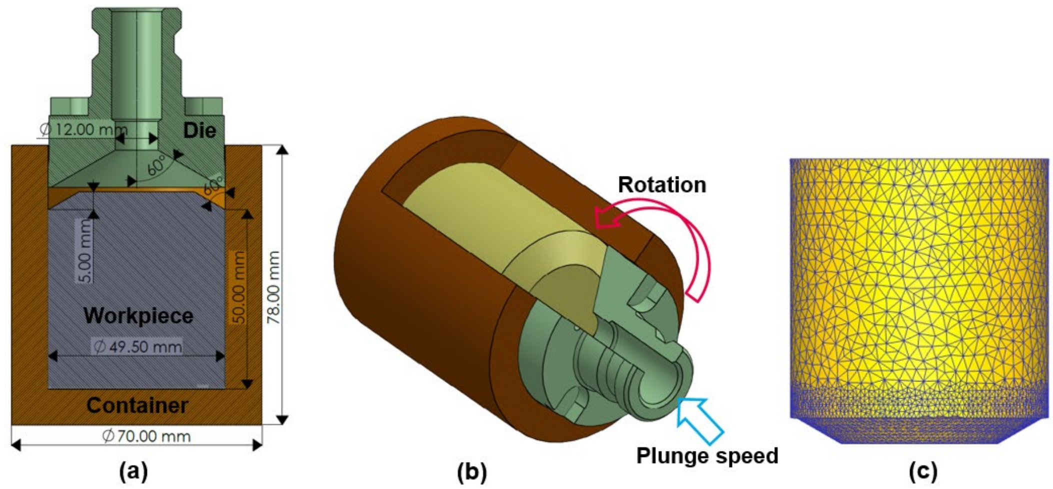

Fig. 3. Process model geometry: (a) Simulation set up and object dimensions; (b) Operational mechanism of FE and; (c) Workpiece showing adaptive mesh and a 60° angle at the edge to improve initial contact conditions.

The Arrhenius equation, relating strain rate, flow stress and deformation temperature, is applied to capture the material behavior during FE [14]. Based on a hyperbolic sine function, the Arrhenius equation can be written as:

$$\underline{\dot{\varepsilon}} = A[sinh\,sinh\,(\alpha\sigma)\,]^{n} exp\left(-\frac{Q}{RT}\right) \tag{1}$$

where $\underline{\dot{\varepsilon}}$ is the strain rate, Q is the activation energy due to thermal deformation, n is the stress exponent, A and α are material constants, R is the gas constant, T represents the temperature and σ the initial flow stress. Flow stress data of AA2024 alloy are deduced from a hot compression test conducted at deformation temperatures between 200°C and 500°C under strain rates of 0.001-10 s^{-1} [15, 16]. The following parameters are used: $A = 1.96 \cdot 10^{8}$ s^{-1}, $\alpha = 0.016 MPa^{-1}$, $n = 4.27$ and $Q = 148$ kJ mol^{-1}. Non-isothermal process conditions are applied for all objects with reference temperature at 20 °C. Other values used in this simulation to relate different thermal interactions between the objects are: 0.02 N s^{-1} mm^{-1} C^{-1} for convection between tools and environment, and 11 N s^{-1} mm^{-1} C^{-1} for conduction between workpiece and tools as recommended for DEFORM 3D forming operations.

After several investigations on the two friction models, i.e. shear and Coulomb, a significant better agreement between experiment and simulation was obtained by modelling the mechanical interaction between the translating die and the rotating container with the workpiece via a Coulomb friction model, where a temperature-dependent friction coefficient μ is used [12], see Table 1.

Table 1. Friction coefficient as function of temperature [12].

Friction coefficient	0.5	0.36	0.3	0.26	0.2	0.1	0.08
Temperature (°C)	20	160	200	300	400	500	600

Although the experiment is performed force-controlled, due to numerical stability reasons, the simulation is performed displacement- or velocity-controlled, respectively. The die speed applied in the simulation is deduced from the die velocity during the FE experiments with the FE100 as shown in Fig. 4, and a rotational speed of 90 rpm is applied on the die.

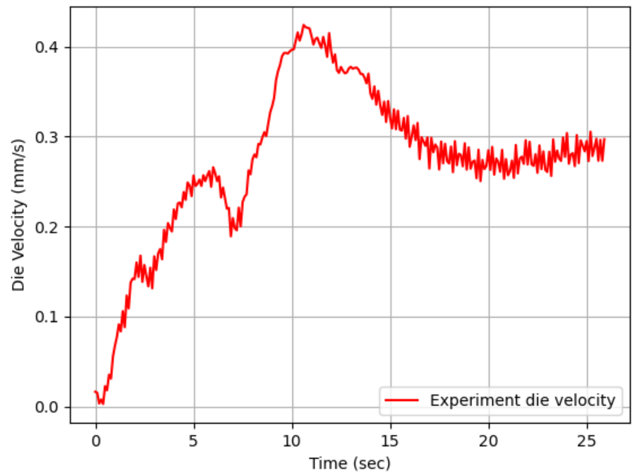

Fig. 4. Experimental die velocity obtained from the force-controlled experiment for ER 25.0 with FE100, which is used as simulation input.

Results and Discussion

As shown in Fig. 5, the results of the velocity-controlled simulation are in good agreement with the force-controlled experiment for both force and thermal history. During the deformation, the rapid increase in force and temperature at the onset of the process is related to the initial "cold" state of the workpiece, i.e. deformation resistance, and filling of the die angle cavity before extrusion. After the initial ramp-up, the process force shows a quasi-steady state due to sufficient material softening achieved.

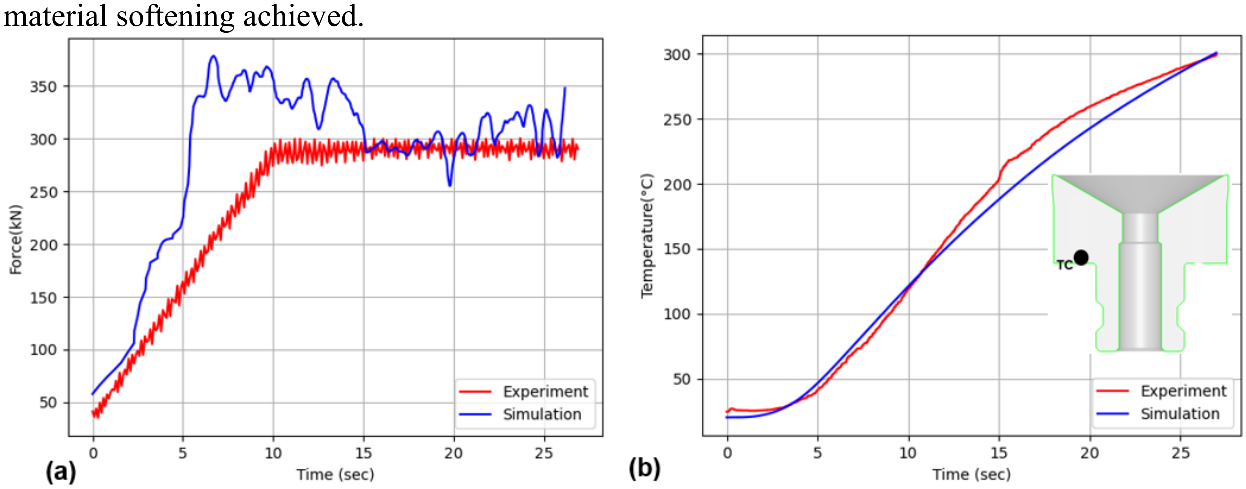

Fig. 5. Comparison between experimental and simulation results for (a) process force and (b) thermal history for ER 25.0.

The generated heat is directly related to the temperature; therefore, material softening depends on the contact condition and mechanical interaction between the workpiece and the extrusion die. Fig. 5 shows the calculated spatial temperature distribution at the interface between the workpiece and extrusion die. The maximum temperature is obtained at the contact layer to the die as shown in Fig. 6, because of the direct interaction between the rotating workpiece and translating extrusion die. The maximum temperature decreases with decreasing extrusion ratio viz, 551°C, 525°C, and 511°C, see Fig. 6(a), (b) and (c), respectively. This effect is attributed to less frictional heat with decreasing extrusion ratio, which is consistent with the findings of Baffari et al. [7] for a 90° die.

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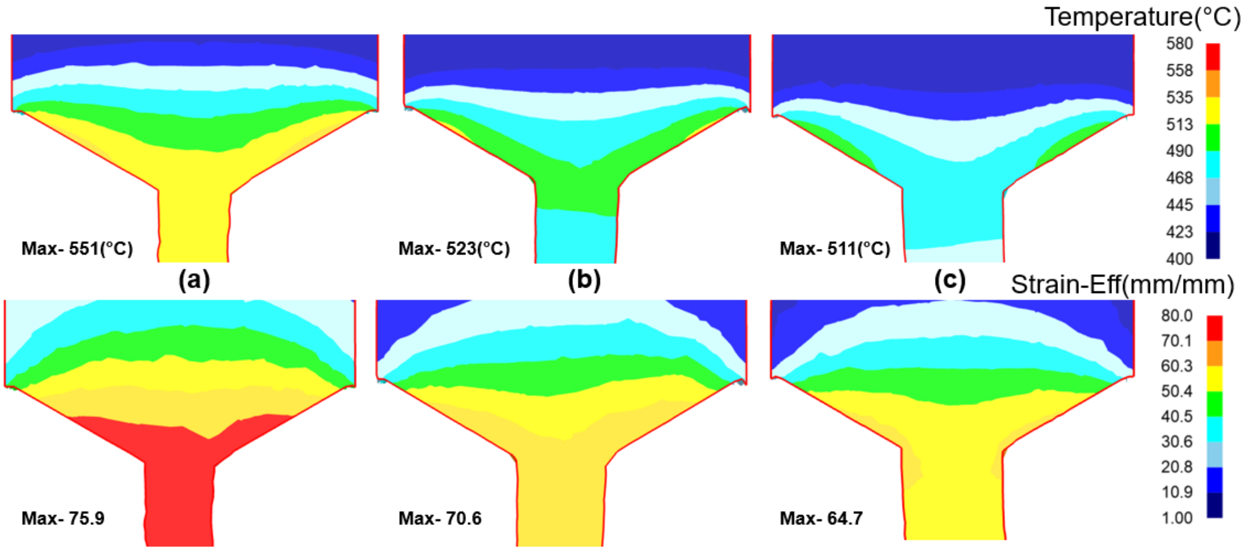

Fig. 6. Spatial temperature and strain distribution results for different extrusion ratios: (a) ER 25.0, (b) ER 17.36 and, (c) ER 12.25.

Next to the temperature, the resulting material deformation plays a crucial role in terms of the resulting microstructure and quality of the extrudate. Fig. 6 depicts that strain values close to the die orifice are higher compared to the rest of the workpiece. This is due to the edge of the die orifice, which induces severe plastic deformation on the workpiece during processing. Consequently, higher extrusion ratios induce more severe plastic deformation leading even to maximum strain values of 75. It is evident that the strain distribution is less homogeneous with decreasing extrusion ratio; see Fig. 6.

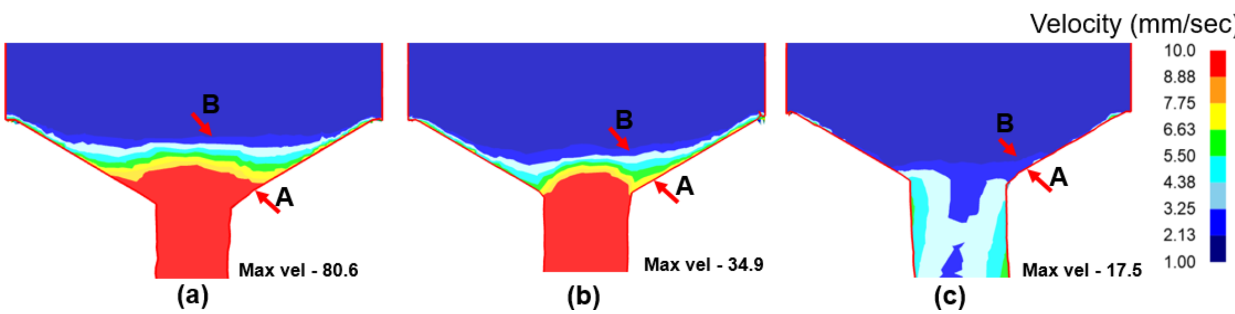

Fig. 7. Material flow velocity for different extrusion ratios: (a) 25.0, (b) 17.36 and (c) 12.25.

In FE, the mechanical interaction between the die and workpiece leads to thermo-mechanical conditions as described above, which are strongly influenced by the transition between the container and die, in particular, the die orifice. A homogeneous material flow is assumed to occur due to homogeneous deformation and, in this regard, better mechanical properties. As illustrated in Fig. 7, a higher probability of homogeneous material flow is observed at high extrusion ratios. The origin of the homogeneous material flow for high extrusion ratios can be traced to more severe plastic deformation induced. As depicted in Fig. 7, the velocity distribution region marked by points (A) and (B) decreases as the extrusion ratio decreases. The non-homogeneous material flow for the low extrusion ratio in Fig. 7(c) is attributed to less deformation due to sliding tendencies between the workpiece and the die.

Summary

The process simulation of the friction extrusion (FE) process accurately predicts the force and thermal history occurring in the force-driven FE experiment. The following conclusions are drawn:

- The maximum temperature is predicted at the contact region between the die and the workpiece for all cases due to direct mechanical interaction.
- Die geometry has a profound effect on the resultant thermo-mechanical conditions.
- A higher extrusion ratio leads to more uniformly distributed and higher values of maximum strain due to increased severe plastic deformation.
- At high extrusion ratios, the material flow is more homogeneous, and therefore a superior properties of the extruded rod could be anticipated.

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Data Availability

The data related to this research is available online (https://doi.org/10.5281/zenodo.7399955)

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