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Investigation of material flow during friction extrusion process

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ABSTRACT

Material flow during a friction extrusion process is investigated. A three-dimensional computational fluid dynamics (CFD) model of the friction extrusion process is proposed with a no-slip contact condition between the rotating tool and the material being processed. In the CFD model, the material considered is aluminum alloy 6061. During processing the material is treated as a non-Newtonian fluid with a viscosity that is temperature and strain rate dependent. As a first model of this process, the focus of the CFD model is to provide initial insights about the material flow field, which can be used to help with the design and interpretation of experiments to measure the flow field. Due to the lack of experimental validation data at this stage, and to provide an understanding of the accuracy and validity of CFD simulation predictions of the velocity field, the same process but with a model fluid and without extrusion is considered. This modified process has been studied analytically, numerically, and experimentally, and CFD simulation predictions have been verified analytically and validated experimentally. Then the full process with consideration of extrusion is modeled using CFD and simulation predictions of the flow field are presented.

1. Introduction

Friction extrusion is a friction based process in which a wire is produced through consolidation and extrusion of precursor materials such as powders and metal chips. A schematic diagram of the friction extrusion process is shown in Fig. 1. The extrusion die rotates about the extrusion axis and is loaded downwards. At first, metal billets (also called billet charge, which is the material being processed) in the process chamber will be consolidated under high pressure. During and after consolidation, friction at the interface between the die and the billets, and severe plastic deformation in the billets, generate a large amount of heat, resulting in a temperature increase in the material. Under high pressure, the consolidated and softened metal will be extruded out through the extrusion hole and form a wire.

Heating from friction and stirring of material created in the friction extrusion process makes friction extrusion different from traditional extrusion (which involves melting of materials). This difference leads to some salient merits compared with traditional extrusion, such as (a) friction extrusion is energy efficient, (b) friction extrusion does not require large loads and hence is easy to realize, and (c) the precursor material can be in the form of low-cost powders (e.g. for titanium) or from machining wastes (metal chips). As a result, it is envisioned that the friction extrusion process can be very useful in many industries (e.g. the aerospace industry) where reduction of machining waste and energy cost is essential in the manufacturing of a large amount of materials.

The friction extrusion process was patented in 1993 by The Welding Institute [1]. However, this process has received little attention and the patent lapsed in 2002. As a result, there has been little scientific understanding of this process in the literature [2]. While at the same time, a similar friction based process, the friction stir welding (FSW) process (see Fig. 2), has been widely studied both experimentally and numerically. A key similarity of the two processes is that the heat source comes from severe plastic deformation in the metal and from the friction between the tool and metal. Another similarity is that the products, i.e. the welded joint and the extruded wire, have a similar thermal–mechanical history and experience an analogous stirring process, which largely affects the mechanical properties of the products.

Due to the similarities between friction extrusion and friction stir welding and the lack of numerical studies of the friction extrusion process in the literature, it is useful to consider relevant modeling and simulation approaches for FSW that may be applicable to friction extrusion. For material flow prediction, both solid mechanics and fluid dynamics based approaches have been applied to FSW modeling. In the solid mechanics based approach (e.g. [3,4]), contact friction between the tool and material is modeled directly and material flow is simulated using the

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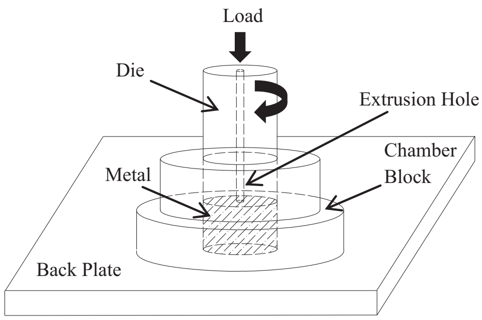

Fig. 1. Schematic of Friction Extrusion Process.

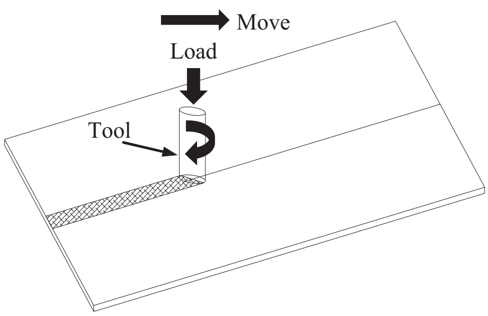

Fig. 2. Schematic of Friction Stir Welding Process.

Arbitrary Lagrangian–Eulerian (ALE) formulation. In the fluid dynamics based approach, contact between the tool and the material is modeled by requiring the material in contact with the tool to rotate together, and material flow is simulated using CFD by treating the material as a non-Newtonian fluid (e.g. [5,6]).

The present work aims at gaining an understanding of the material flow field in the friction extrusion process. Towards the goal of developing a full three-dimensional (3D) CFD model of the friction extrusion process, a two-step approach will be employed. First, a modified process is created to allow the verification of simulation prediction by an analytical solution and the validation of the analytical solution and CFD model prediction by experimental measurements. In the modified process, (a) a transparent model fluid (instead of a metal) is used as the material so that the motion of marker particles in the fluid can be observed from the outside of a transparent process chamber, and (b) the extrusion portion of the process is not included so that only the flow in the process chamber due to the rotating motion of the tool at the tool-material interface needs to be considered. This modified process enables a precursor study of the full process, so that an analytical solution can be obtained for the verification of CFD simulation predictions.

Both the analytical and numerical solutions for the modified process are included in this study due to several considerations: (1) the analytical solution is needed to serve the role of verifying that the numerical solution method is adequate for producing converged and accurate solutions for the friction extrusion process, (2) for comparisons with experimental measurements, it is easier to process the analytical solution to provide a direct comparison with the measured data, and (3) because the analytical solution is obtained under idealized conditions, numerical solutions are needed for more realistic situations that are more relevant to the actual friction extrusion process.

An experimental study of the modified process is carried out simultaneously, in which marker particles and a digital particle tracking system are used to provide measurements of the velocity field in the process chamber, so that validations of CFD simulation predictions and the analytical solution can be made.

Second, after an understanding of the accuracy of the CFD model is established based on the modified process results, a 3D CFD model of the friction extrusion process for a metal (aluminum alloy 6061) will be proposed to provide initial insights for the process, which will be useful in helping with the design and interpretation of experimental measurements for material flow fields for the friction extrusion process. Simulation predictions of the 3D CFD model will include the velocity field, fluid particle path lines, strain rates and viscosity variations in the process chamber.

The remaining sections are arranged as follows. In Section 2, first an analytical solution of the velocity field is obtained for the modified process; then the modified process is simulated using CFD to predict the velocity field, which is compared with the analytical solution for verification; and then an experiment for the modified process is developed to measure the velocity field using marker particles, which provides a validation of the analytical solution and CFD prediction. In Sections 3, a 3D CFD model for the friction extrusion process of aluminum alloy 6061 is developed and the velocity field is predicted, and features of the velocity field are discussed. Finally, in Section 4 conclusions from this study are summarized. All CFD simulations are carried out using the FLUENT software.

2. The modified process with a model fluid and without extrusion

Fig. 3 shows a schematic diagram of the modified process. A cylindrical chamber with a height of H and an interior radius of R is filled with a viscous model fluid. A cylindrical die comes into contact at the top surface of the fluid. When the die rotates at an angular speed of ω, the liquid at the contact interface will rotate at the same angular speed due to the viscous nature of the fluid, thus providing a no-slip contact boundary condition for the fluid volume at the contact interface. Compared with the friction extrusion process, the modified process considers the fluid motion due to tool rotation but not due to extrusion, so that an analytical solution can be obtained to provide verification for the CFD simulation prediction.

The model fluid used in this modified process is an incompressible and highly viscous Newtonian fluid (instead of a non-Newtonian fluid) with a constant viscosity μ, which also enables the availability of an analytical solution. More details of the model fluid will be described in Section 2.3 since this model fluid will be used in an experiment to allow measurement of the velocity field in the modified process.

Besides the no-slip boundary conditions at the die–fluid interface, the other boundary surfaces (the vertical cylindrical surface and the bottom surface) of the process chamber are also taken to have the no-slip boundary conditions. As such, at the die–fluid

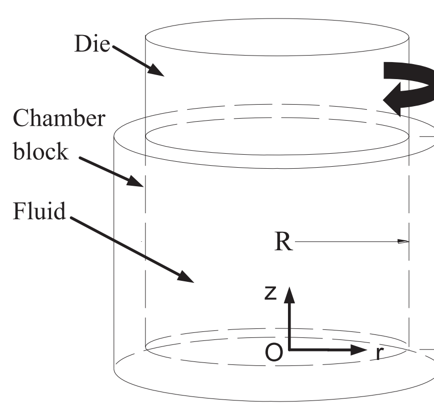

Fig. 3. The modified process.