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Strain and texture in friction extrusion of aluminum wire

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ABSTRACT

Friction extrusion is a solid-state process that can produce high quality, fully consolidated wire or rod directly from metal chips, powder or billet. However, little is understood regarding the variation in material flow or extrusion strain with changes in processing parameters. Extrusion strain level may be of great import in determining whether or not the charge is fully consolidated. In order to explore the material deformation behavior during this process, flow visualization experiments were conducted using AA6061 billets with AA2195 as a marker insert. Variations in material flow during a single extrusion were documented and correlated with changes in grain size, which has previously been correlated with extrusion temperature. Marker shape was used to make an approximation of imposed strain during the extrusion as a function of relative extrusion temperature. Also, tests using various extrusion forces and die rotation speeds were conducted. The influence of extrusion parameters on deformation evolution was elucidated and discussed. Grain orientation analysis conducted using electron backscatter diffraction showed a fully recrystallized microstructure with weak texture indicating that recrystallization was likely a static process occurring after passage of the wire through the die. Key findings include: (1) longitudinal strain is solely a function of overall reduction (2) in plane shear strain decreases with increasing extrusion temperature, and (3) with increasing extrusion temperature, friction extrusion becomes similar to normal extrusion.

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1. Introduction

Friction extrusion (FE) was invented at The Welding Institute (Cambridge, UK) in the early 1990’s and subsequently largely ignored. It was first derived from friction stir processing as a method of forming or reforming metal/ceramic composite material (Thomas et al., 1991). It is related to simple extrusion processes with the primary difference being that the extrusion die rotates about the extrusion axis and the die is required to impart substantial deformation to the initially finely divided charge (like metal waste or chips), in order to consolidate it prior to extrusion, see Fig. 1. Furthermore, the extrusion billet and extrudate may be heated only by dissipation of plastic work or by auxiliary heating in addition to the plastic deformation heating. For initially unconsolidated charges, the shearing and heating due to dissipation of the plastic deformation imparted by the rotating die leads to consolidation and subsequent extrusion of the feedstock material. As with other friction-based processes, FE is a nominally solid-state process with peak process temperatures below the bulk melting point of the material being processed. This process is well suited for creating solid wire/rod from particulate materials such as metal powder or machining chips. As such, one of its primary applications may be in the recycling of otherwise low values material streams. The process may also be of value for the production of small lots of custom composition wires for either welding or wire-arc additive manufacturing feedstock. The plastic deformation associated with the friction extrusion process should provide a strong homogenizing effect to the initial extrusion charge (Li et al., 2015). Due to this homogenizing effect, wire with customized chemical composition may be made by extrusion of rather poorly mixed starting components or directly from as cast billets. Since the process depends of plastic deformation for homogenization and consolidation, it is important to understand, as quantitatively as possible, how the various process parameters affect the level of deformation imparted to the charge prior to extrusion. Such quantification has not been published in the open literature as of this writing.

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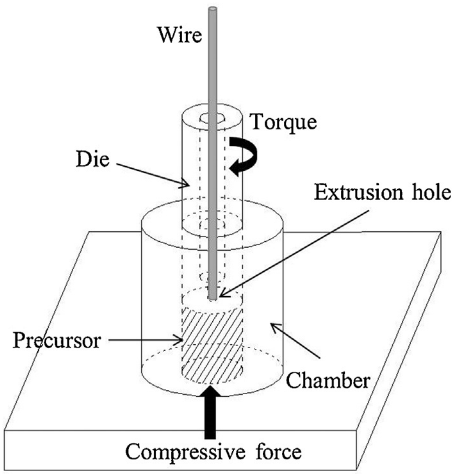

Fig. 1. Schematic diagram of friction extrusion process.

2. Background

While quantification of deformation levels in friction extrusion has not been published, there is some related work in the literature. Direct recycling of aluminum chips via hot extrusion was first proposed and patented by Stern (1945). Gronostajski and Matuszak (1999) comminuted and compacted aluminum chips followed by conventional hot extrusion. This solid state process avoids formation of thick oxide skin so the scrap can be converted to a finished product without further processing. The process was also used for the development of novel alloy compositions based on the blending of multiple alloy particulates. Recent study indicates that high quality extrudates can be produced when appropriate die design criteria are satisfied (Misiolek et al., 2012). Tekkaya et al. (2009) shows that the pre-compaction step is not important when minimum stress, strain, and temperature conditions are achieved for creating metallic bonding between chips. Haase et al. (2012) use the integrated equal channel angular pressing (iECAP) die instead of the flat-face or the porthole die as a tool for solid state recycling of aluminum machining chips. Since additional shear deformation and strain are introduced, improved chip bonding and superior strength and ductility are achieved. McDonald et al. (2014) also use ECAP to recycle Ti-6Al-4V machining chips to produce fully dense bulk material. Compared with commercial Ti-6Al-4V, better mechanical properties are achieved after mill-annealing treatment. Güley et al. (2013) studied the welding quality of using flat-face die and porthole die via conducting experiments and numerical simulation. The bonding criteria of chips and the break down mechanism of oxide layer were established. The welding quality index (WQI) related with normal pressure and effective stress has been proposed. Cooper and Allwood (2014) reviewed previous theoretical and experimental work on solid bonding. The summation of experiments show that a minimum strain is required for bonding. Increasing the temperature, normal contact stress or shear stress can reduce this required minimum strain. A normal contact stress above the materials' uniaxial yield stress is necessary to produce a strong bond. Haase and Tekkaya (2015) further processed hot extruded chips by backward can extrusion or forward rod extrusion. By comparing the microstructure and result of mechanical tests, it was shown that the deformation route during hot extrusion is critical to high quality finished products. Duflou et al. (2015) discussed the significant environmental impact reduction associated with solid state recycling processes. 4% less material loss were documented for screw extrusion when considering average industrial material loss fraction.

Using a principle similar to that of friction extrusion, a testing machine using combined pressure and shear to granulate and recycle aluminum was built by Widerøe et al. (2010). Their results indicated that the shear deformation greatly reduced the axial force required for compacting aluminum scrap. Also, they showed that the number of revolutions of the tool influences deformation penetration depth and mixing range. Since limited experimental parameters were used, the relationships between control parameters and process responses such as material flow pattern and microstructure were not determined. Widerøe and Welo (2013) observed spiral core path as a possible material flow path in screw extrusion. Their result indicates that the highest rate of material flow was found in the center of screw channel and dead metal zones were located at the bottom of the screw channel and toward the container wall.

The above studies show that extrusion at high temperature is not only an economical avenue to recycle aluminum chips but also a route to produce high quality finished products. Compared with traditional hot extrusion, friction extrusion requires considerably smaller extrusion force to produce high deformation and strain. Also, chamber preheating is avoided, so energy, time and capital can be conserved.

With regard to friction extrusion work, Tang and Reynolds (2010) produced AA2050 and AA2195 wires from chips via friction extrusion. The extrusion rate was simply related to power input and die rotational speed. A fully equiaxed, recrystallized microstructure in the extruded wire was observed. However, material flow patterns were not elucidated. Metallographic study and hardness testing of the extruded wires indicated equiaxed, fine grain structure on both longitudinal and transverse cross sections as well as uniform hardness distribution from wire center to edge. It is apparent from the literature that the level of strain during extrusion is critical for achieving good bonds between initially unbounded scrap or extrusion charge. Hence, it is important to understand how the strain evolves during friction extrusion so that optimum process parameters may be adopted.

Marker insert studies have been used for studying material flow in several metalworking processes. Key to use of marker inserts to study flow are different etching characteristics between marker and parent metal and similar flow stress of marker and parent metal at relevant temperatures. For example Valberg studied material flow in direct extrusion of an Al–Mg–Si alloy using AlCu 2.5 indicator pins inserted into a billet in a grid pattern (Valberg, 1992). Widerøe and Welo (2013) developed a novel contrast material technique to visualize the material flow in the screw extrusion process. Seidel and Reynolds (2001) successfully applied a marker insert technique to illustrate the material flow in the friction stir welding process. In each case, the flow pattern is elucidated after processing by serial sectioning and etching. By applying a similar marker insert technique, (Li et al., 2013) showed that the die geometry in friction extrusion has an effect on the material deformation during FE but does not fundamentally modify the flow patterns or consolidation mechanism. However, the influences of extrusion force and rotational speed on the flow patterns in the friction extrusion process have not been studied and in no prior work has the strain level been quantified.

Previously, a series of experiments was performed and finite element simulations were carried out for studying the material flow and temperature evolution during friction extrusion. Zhang et al. (2014) established a three-dimensional computational fluid dynamics model for the friction extrusion process. A similar model was used to investigate material flow and compared with experimental results (Zhang et al., 2015). Zhao et al. (2014) performed a physical simulation of friction extrusion using syrup as a working fluid and image correlation to track the motion of solid particles in the fluid. Zhang et al. (2015) also studied heat transfer phenom-

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