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Characterization of the deformation field in large-strain extrusion machining

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ABSTRACT

Large-strain extrusion machining (LSEM) has been emerged as a promising severe plastic deformation methodology for the creation of nano or ultra-fined grained materials. To realize deformation control, the key issue involved is the strain estimation in LSEM. In order to characterize the deformation field in LSEM, the experiments of LSEM oxygen-free high-conductivity copper were conducted by using a specially designed LSEM device. Based upon the deformation field measured by high speed imaging and digital image correlation (DIC), a new strain estimation model considering the extrusion process of constraint is proposed in this paper. The theoretical predicted strain agrees well with the measurements.

1. Introduction

Metal cutting, simply machining, is a process of removal of excess material from the workpiece in the form of chips. Over the past decades, Oxley (1989) and Shaw (2005) have been carried out a series of work to discover the fundamental mechanisms underlying the metal machining processes. According to the extensive study of Childs (2013), machining has been proved to be a particularly effective method to achieve severe plastic deformation (SPD). Compared to the conventional SPD methods such as equal channel angular pressing (Segal et al., 1981), high pressure torsion (Smirnova et al., 1986) and surface mechanical attrition treatment (SMAT) (Tao et al., 2002), the SPD method of machining needs only one single pass of deformation process to produce large strains in removed chips and high strength materials are much easier to be deformed in this manner. Materials undergoing SPD often result in the variation of microstructure within the materials in the work of Mueller and Mueller (2007). Recently, Güzel et al. (2012) researched dynamic grain structure evolution of materials in SPD and found that grain size decreases with increasing equivalent plastic strain. According to the study of Lu et al. (2004), the materials with SPD have enhanced mechanical properties with raising both the strength and the thermal stability. Yan et al. (2012) further found that strength and ductility are both increased by means of SPD with high strain rates. As for the SPD of machining, Brown et al. (2002) first used the low-cost method to produce nanostructured materials. Shankar et al. (2005) and Swaminathan et al. (2005) then applied the machining method to study microstructure refinement as a function of deformation condition for different metals. Deng et al. (2009) further developed a realistic finite element model to research the relationship between the formation of ultra-fine grained materials by machining and large shear strain imposed in deformation fields. In the previous studies, a relatively low cutting speed is applied to avoid the thermal effect on the produced microstructure during machining. Recently, even with very high cutting speed, Kanani et al. (2014) found that it is possible to produce continuous chip with a stable nano-and ultra-fine grained structure by choosing a proper machining condition. Therefore, machining is a promising SPD method to produce materials with enhanced mechanical properties by controlling the level of SPD in machining.

The level of strain in SPD machining is constant if the machining parameters (rake angle and precut chip thickness) are given in advance. In order to control the level of deformation in machining, De Chiffre (1976) first puts forward the extrusion-machining process and made use of the process to produce materials of different mechanical properties by changing the controlled chip thickness ratio. After three decades, Moscoso et al. (2007) perform seminal works where large-strain extrusion machining (LSEM) is developed to create nano or ultra-fined grained materials. LSEM is an improved technique of SPD machining. Compared with the conventional SPD machining, LSEM can control the level of

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deformation even if the rake angle and precut chip thickness are given in advance. Saldana et al. (2010) further find that the chips' microstructures and properties are tightly related to the controlling plastic deformation in LSEM. The experiments of Moscoso et al. (2007) and Saldana et al. (2010) have shown that LSEM can be applied to a variety of metals (e.g., copper, titanium, Al6061-T6) for producing UFG microstructures. Particularly for copper, an elongated UFG microstructure is obtained at the shear strain level of 2.2 in LSEM, and a mix of elongated and equi-axed UFG microstructure can be seen in materials at the shear strain level of 4.3 in LSEM, and the essentially equi-axed UFG structures with nano-size grains ($\sim$250 nm) can be produced if the level of shear strain in LSEM is above 7.4. Brown et al. (2009) observe the increase in the proportion of high angle boundary misorientation with increasing strain at small deformation rates, which results in the grain refinement in LSEM. The microstructure in UFG materials is directly related to the level of strain in LSEM. Therefore, in order to control the microstructure in UFG materials much better, it is crucial to determine the plastic strain during LSEM in advance. Based on the single shear-plane model, De Chiffre (1976) derived an expression of shear strain in primary shear zone in chips in LSEM, where the constraint effect during extrusion machining was neglected. However, the recent measurements of the deformation field in LSEM made by Guo et al. (2012) and Efe et al. (2012) using high speed imaging and particle image velocimetry (PIV) have demonstrated that the difference between the PIV measured strain and the Chiffre's model predicted strain becomes more prominent with decreasing the chip thickness ratio. Hence, to obtain reasonable strain estimation in LSEM, the effect of the chip thickness ratio or the geometrical constraint should be incorporated.

In this paper, in order to investigate the effect of the geometrical constraint on the strain field during LSEM, a commercial grade oxygen-free high-conductivity (OFHC) copper (99.95%) was machined at different levels of strain by using a specially designed LSEM device. By making use of high speed imaging and digital image correlation (DIC), the detailed features of the material particle flow field in chip in LSEM were measured. Based on the experimental observation, an explicit expression of shear strain in LSEM is presented in the paper where the extrusion constraint effect during machining process is included. The predicted strains are consistent well with the present experimental results and the other available measurements.

2. Experimental procedure

The sample materials used in the experiments is oxygen-free high-conductivity (OFHC) copper (99.95%) with chemical composition specified in Table 1. The annealing temperature of OFHC is 375–650 °C. The samples were taken from OFHC copper bar and the microstructures of three section planes in the workpiece are shown in Fig. 1.

Fig. 1 shows the device of LSEM which is conducted on material testing machine. The chip thickness t_c is controlled by the constraint in LSEM. Fig. 2 shows a schematic of LSEM, in which the free machining (FM) is marked by the dashed lines. Here, an orthogonal machining process is taken into consideration, where a wedge-shaped tool with a rake angle α is static, and the workpiece with a precut depth t_0 is moving toward the tool at the cutting speed V. According to the books of Oxley (1989) and Shaw (2005), it is assumed that the pure plastic deformation happens in machining. Based on the tensile tests of OFHC copper in Appendix A, the elastic strain is less than 0.5% but the plastic strain in LSEM is more than 100%. It is reasonable to ignore the occurrence of elastic strain and subsequent recovery in LSEM. Here, the elastic deformation is ignored and the pure plastic deformation is assumed in LSEM. In this process, the workpiece materials in the cutting layer flow out along the rake face of the tool in the form of a chip with a thickness t_c. The levels of large plastic strain in LSEM are controlled by the chip thickness ratio ($\lambda = t_c/t_0$). The chip is formed by a process of shear which is approximately confined to a single plane called shear plane OA. The inclined angle φ of shear plane is named as

Table 1
Chemical composition of oxygen-free high-conductivity copper (99.95%).

Elements	Cu + Ag	Fe	S	Pb	Zn	Sn	O	Others
Wt.(%)	99.97	0.004	0.004	0.003	0.003	0.002	0.002	0.01

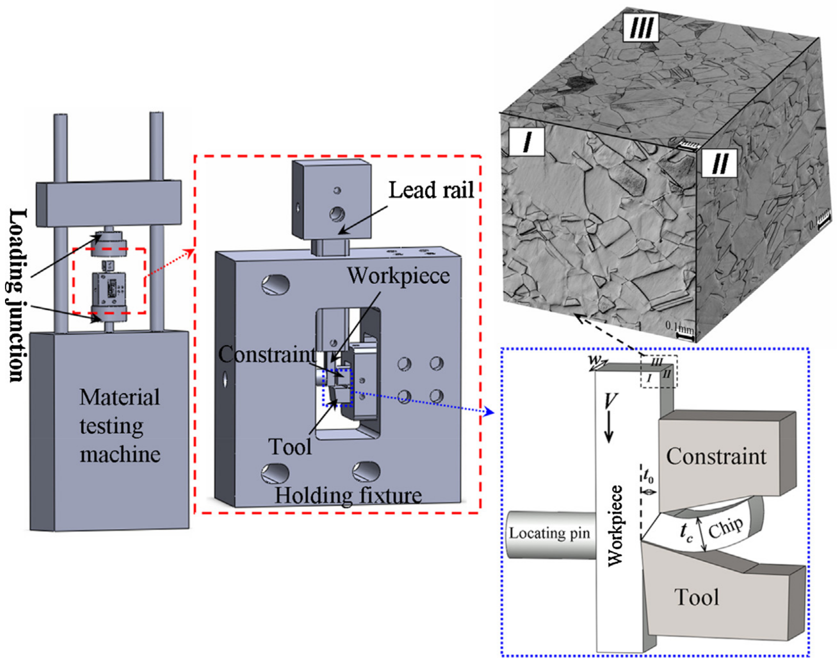

Fig. 1. Schematic of LSEM processes and the microstructures of three section planes I, II and III of workpiece.