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Finite element analysis of the plastic deformation in tandem process of simple shear extrusion and twist extrusion

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ABSTRACT

Recently, simple shear extrusion (SSE) and twist extrusion (TE) are introduced to fabricate ultrafine grained bulk rod metallic materials. The SSE and TE processes generate significant deformation inhomogeneity, with higher and lower strains in the center, respectively, which easily causes mechanical instability of the materials. In this study, to overcome this deformation inhomogeneity problem in SSE and TE, a tandem process of SSE and TE (TST) is suggested. The finite element method is applied for plastic deformation behavior during the TST process. The results demonstrate that the TST process can produce relatively homogeneously deformed materials. In particular, the effects of back pressure and processing order on the plastic deformation behaviors in the TST process are systematically analyzed.

1. Introduction

Over the last two decades, ultra-fine grained materials, polycrystalline materials with grain size less than 1 μm, have been extensively developed due to their outstanding mechanical properties [1–3]. In order to fabricate the bulk ultra-fine grained metallic materials, various severe plastic deformation (SPD) processes [4–7] were proposed: multiple forging, the cone–cone method [8], equal-channel angular pressing [4,9–12], accumulative roll bonding [13–15], constrained groove pressing [16,17], and high-pressure torsion [18–20]. The SPD techniques successfully enhanced multi-functional material properties by imposing high shear strain. Numerous researchers have investigated strain distributions of the SPD processes using theoretical analyses, typically the finite element method (FEM) [9,19,21–24].

However, the above-mentioned conventional SPD processes have some limitations. Firstly, the SPD-processed workpiece exhibits heterogeneous mechanical properties and microstructures due to its inhomogeneous plastic strain distributions developed during the SPD processes [20,25]. Secondly, the SPD-processes produce too small of a workpiece for industrial applications. Therefore, ultra-fine grained materials still need more development in terms of upscaling and deformation uniformity, although they have good mechanical properties after grain refinements.

In order to overcome the upscaling and industrialization problems, several conventional extrusion-based SPD processes have been proposed. Simple shear extrusion (SSE) [26] and twist extrusion (TE) [27–30] are such processes to fabricate ultra-fine grained materials using the extrusion-based processes. Fig. 1(a) represents the concepts of the SSE and TE processes and the combination process of SSE and TE. The SSE and TE processes have specific die shapes for imposing shear deformations. Firstly, the SSE process has a quasi-simple shear shape in a channel, and the workpiece is distorted up to $1/4\pi$ and returns to the initial shape. Secondly, the TE process has the same initial and processed geometries of the workpiece, following the helix path in the TE channel. Schematics of the SSE and TE are presented in Fig. 1(b). The SSE process imposes quasi-simple shear deformation during the process. The cross section of the specimen changes to the parallelogram shape at the middle stage, and returns to its initial shape. Contrary to the SSE process, the TE process imposes torsional shear deformation and the specimen rotates during passing the helical shaped die, and the shape of specimen maintains its initial shape. Theoretically, the deformed shapes of the workpieces in both the SSE and TE processes maintain their initial rectangular shapes when the specimen passes out through the channels; hence, we can repeat the processes without additional interprocessing treatments.

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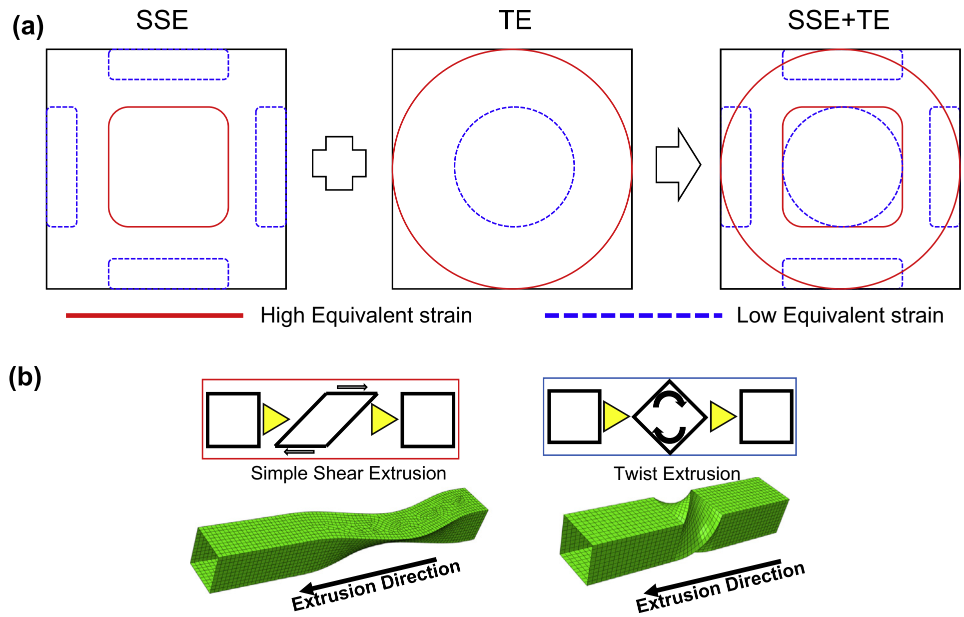

Fig. 1. (a) Concept drawing of the combined SSE and TE process (Red solid line: High equivalent strain region, Blue dashed line: Low equivalent strain region) and (b) schematics of SSE and TE. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

However, each of the TE and SSE processes still generates inhomogeneous strain distribution, as many of the other SPD processes do, and this results in mechanical property instability. Interestingly, the strain distributions in the SSE and TE processes have a specific tendency, depending on their deformation characteristics. In the SSE process, deformation is accumulated in the center area of the specimen, but in the TE process, large deformation is imposed to the outside of the specimen, as can be seen in Fig. 1(a). Therefore, if we combine both the SSE and TE processes, we may be able to produce homogeneously deformed specimen by compensating the local less deformation of one process for the other process.

In this paper, we propose the tandem process of SSE and TE processes, TST, shown in Fig. 1 with schematic equivalent strain distributions. It is expected that the strain in the TST-processed material will become homogeneous by combining the two inhomogeneous processes. The finite element analyses were employed to understand the deformation characteristics of the specimens during the TST process. In particular, the effect of back pressure [31,32] was analyzed.

2. Finite element analyses procedure

In the finite element simulations, a 10 mm × 10 mm cross section of a 30 mm-long billet of commercially pure aluminum (AA1050) was used. The processing conditions are based on the previous research [26]. The first step is SSE, and the second step is TE. In the SSE part, quasi-simple shear deformation proceeds up to $1/4\pi$ (45°) in a 60 mm-long deformation zone. In the TE part, the deformation zone is twisted along the 45° helix path and 10 mm long.

A three-dimensional finite element analysis was performed using ABAQUS 6.9, the commercial explicit code, with C3D8R elements for the specimen. In order to ignore very small deformations in the equipment, we assumed that all of the equipment (dies and anvil punch) were rigid bodies. In addition, the friction coefficient of the interfaces between the billet and die were assumed to be 0.1. In order to analyze the back pressure effect, various back pressure values (0, 50, 100, and 150 MPa) were applied to the opposite (exit) side of the specimen. The material property of the aluminum was shown in Fig. 2 from Ref. [26].

3. Results and discussion

3.1. Separate SSE and TE processes

Fig. 3 exhibits the deformed geometries with equivalent plastic strain distributions in the end sections of the SSE-processed specimen under various back pressure values. The theoretical equivalent strain for a simple shear of 45° is $\tan(45°)/\sqrt{3} = 0.577$. Hence, the theoretical equivalent plastic strains in the middle and end sections are 0.577 and 1.155, respectively, which are in agreement with the values in the center regions in Fig. 3. However, strain distributions are highly nonuniform: the strain values in the central region are nearly the same as theoretical ones and there are low strains in the outer regions. This nonuniform strain distribution is opposite to that of the torsional deformation. This inhomogeneous strain distribution indicates that the deformation mode of the SSE process is not a simple shear, as the name "SSE" indicates. It should be noted that ideal simple shear

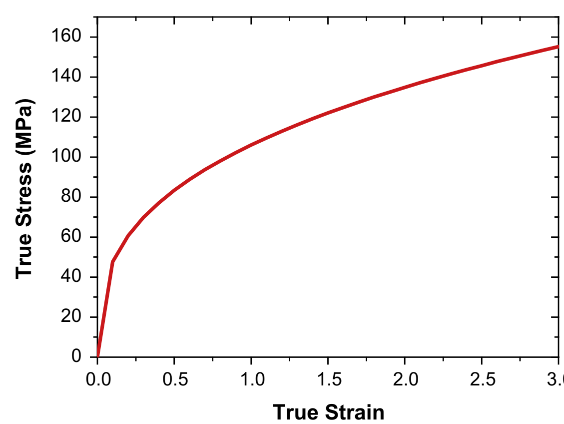

Fig. 2. Stress–strain curve for AA1050 from reference [23].