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Gradient structure produced by three roll planetary milling: Numerical simulation and microstructural observations

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ABSTRACT

In this study a gradient grain structure was produced by processing rod billets through three roll planetary milling (also known as PSW process). This kind of gradient structure is reported to provide an excellent combination of strength and ductility owing to an ultrafine-grained surface layer and a coarse-grained interior of the billet. Specifically, copper rod samples were subjected to up to six passes of PSW at room temperature. To study the evolution of the microstructure during the deformation, microhardness measurements and Electron Backscatter Diffraction (EBSD) analysis were performed after one, three and six passes. Additionally, the distributions of the equivalent stress during PSW and the equivalent strain after processing were studied by finite element analysis using the commercial software QFORM. The results showed the efficacy of PSW as a means of imparting a gradient ultrafine-grained structure to copper rods. A good correlation between the simulated equivalent strain distribution and the measured microhardness distribution was demonstrated.

1. Introduction

Nanostructuring of metallic materials is an effective way to enhance their mechanical properties and performance, which has generated burgeoning research in this area [1]. This widely used approach follows from the well-known Hall–Petch equation [2–4] that establishes a relation between the yield stress and the grain size. However, the improvement in strength is typically accompanied by loss of ductility and therefore limits the application of these materials in industry [2]. Several strategies to enhance both strength and ductility were proposed. For instance, Lu et al. [5] developed nanotwinned structures comprising relatively coarse grains with embedded nanoscale twins. Another strategy widely discussed in literature is related to the fabrication of ultrafine-grained/nanocrystalline metals with a bimodal grain size distribution [6,7]. Recently, an alternative way of producing grain size gradient structures with extremely fine grain size in a near-surface layer and the coarse-grained interior has gained popularity [3,8,9]. It was reported that such gradient nanostructured materials exhibit both exceptional strength and ductility [9,10]. Several processing routes such as sandblasting [11], surface mechanical grinding treatment (SMGT) [3,4] and surface mechanical attrition treatment (SMAT) [10,12] were proposed as viable tools for industrial implementation.

In this work we consider an industry scalable process, namely, three roll planetary milling [13,14] as a way to produce such grain size gradient structures. This process is commonly referred to as PSW – an acronym for the German term Planetenschrägwalzen [13–15] – which is adopted below. The PSW equipment consists of three conical rolls, an external ring and a mandrel. Fig. 1 depicts an arrangement of inclined rolls whose axes intersect that of the billet at a certain offset angle (α) and an inclination angle (β). Adjustment of the positions of the rolls by changing two angles or the length of the supporting axles of the rolls results in adjustable dimensions of the products. As the rolls rotate, the billet moves forward under a screw deformation which allows a large area reduction (e.g. ~96% in [16]) to be imparted on the billet in a single pass. Heat generated by this large plastic deformation and friction may lead to the occurrence of dynamic recrystallization [17]. Thus the PSW process makes it possible to produce materials with a fine-grained structure and enhanced mechanical properties, without any extra heat treatment. The elimination of the external heating of the billets prior to PSW

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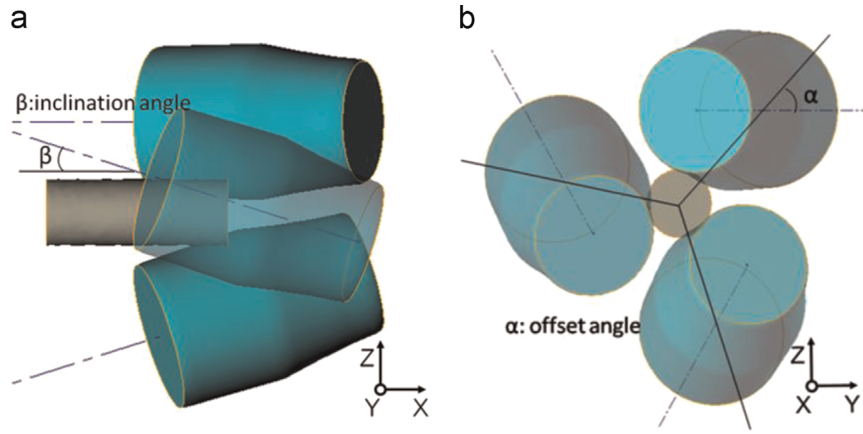

Fig. 1. The arrangement of the rolls from the end view of a PSW rig.

deformation permits a power saving of about 30% in industrial processing [18]. Moreover, PSW mills, as a replacement of six to eight conventional mills in the roughing rolling process [13,19], have some other merits, for example, high efficiency of production, less required plant space and a lower cost of operation and maintenance. Due to these substantial advantages, the PSW process has been widely used in industry to produce stainless steel rods [13], as well as Cu [14,20] and metallic multicomponent materials, such as Al/Cu tubes [21]. However, it should be noticed that the grain size of the bulk of the products processed by PSW may turn out to be relatively large, around tens of microns, as reported in our previous publication [22] and by others [14,23]. Thus, careful control over processing parameters is required to enhance the mechanical properties of the material through PSW processing.

Our recent investigation [24] on the applicability of this process to alter the mechanical properties of pure magnesium has demonstrated the potency of PSW as a technique to achieve strength enhancement. A substantial grain refinement was attained in magnesium without sacrificing its tensile ductility. In the past, studies of PSW processing focused on process parameter optimization using experimental and numerical techniques [13,15,19,25]. The current work aims at investigating the capability of the PSW process to produce a gradient grain structure. Multiple passes are employed to modify the microstructure of pure copper and the mechanical and microstructural evolution of the material as a function of number of passes are reported. The experimental work is complemented with finite element modeling of the process to gain a better understanding of microstructural changes during multiple passes of PSW.

2. Experimental material and methods

Pure (99.9 wt%) Electrolytic Tough Pitch (ETP) copper rods with the diameter of 25.4 mm and the length of 150 mm annealed for two hours at 600 °C were used. Different numbers of passes of PSW were imposed on the billets at room temperature at a rolling axial speed of 120 rpm. No lubricant was used. The offset angle (α) and the inclination angle (β) were 20° and 70°, respectively. A similar level of reduction in billet diameter between successive passes was achieved. Disk-shaped slices were cut out from the billets after one, three and six passes of PSW along the cross-section with the final diameter for each condition of 22, 20 and 16 mm, respectively. The corresponding rolling reductions were about 25%, 38% and 60%. (The rolling reduction is defined as $(D_0^2 - D_f^2)/D_0^2$, where D_0 is the initial and D_f is the final diameter of the billet, respectively.)

The microstructural characterization and hardness measurements were carried out on these samples. A scanning electron microscope (JEOL JSM-7001F FEG SEM) equipped with the Oxford Instruments HKL Channel 5 software package was adopted to perform microstructural characterization. Microhardness measurements were conducted on a Duramin A-300 hardness tester with a load force of 300 g and holding time of 10 s applied. To achieve the hardness distribution mapping, at least 200 indentations were made for each sample with an interval of 0.5 mm and 30° between the measurement positions along the radial and rotation directions, respectively.

The numerical simulation of the PSW process was performed using the Finite Element (FE) package, QFORM7 [43]. This package is specifically designed to simulate metal forming operations and uses an advanced approach which combines the advantages of Voronoi Cells and Finite-Element Methods. QFORM7 offers several benefits, such as the availability of automatic re-meshing and advanced algorithms for solving coupled mechanical and thermal problems, as well as an extensive database of industrial equipment and a materials database. The simulation of the PSW process of copper rod was set up as a full 3D general forming simulation coupled with a thermal problem. The geometry and arrangement of the three rolls as well as the undeformed copper rod are shown in Figs. 1 and 2(b). The rolls were treated as non-deformable rigid bodies and were modeled as rotational drive with an axial speed of 120 rpm. The billet was pressed with a constant speed of 50 mm/s. The true stress–true strain curves for high-speed uniaxial tensile deformation shown in Fig. 2(a) were used to describe the deformation behavior of copper during the PSW simulations.

The rolls and the billet were discretized using tetrahedral elements. The initial number of the elements of the billet was 3307, while each of the rolls was discretized with around 7000 elements, as shown in Fig. 2(b). QFORM7 software utilizes automatic re-meshing algorithm which refined the mesh of the billet during the simulation in regions of higher deformation.

After simulation of each pass, the deformation history was passed on to the subsequent simulation and the location of the rolls was adjusted to produce a reduction in diameter of the billet equivalent to the one obtained in the experiments. The simulations were conducted for room temperature conditions and it was assumed that the temperature history observed during one pass would not be passed on to the next pass, as adjustment of the rolls in the actual experiments allowed for cooling of the billet back to room temperature.