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A new severe plastic deformation method by repetitive extrusion and upsetting

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ABSTRACT

A novel ultra-high straining process, based on the combination of conventional direct extrusion followed by the upsetting of a cylindrical rod in several cycles of severe plastic deformation (SPD), is presented. This procedure, called repetitive extrusion and upsetting (REU), begins with the extrusion in order to elongate the grains. After extrusion, the specimen is upset until the initial diameter is reached again, so the direct extrusion process can be repeated. During extrusion and upsetting processes, the grains are fragmented along shearing planes. Four cycles of successive REU have been applied to commercial purity aluminum. The effective strain and the potential for grain refinement were evaluated. Preliminary microstructure investigations and mechanical properties evaluation of the processed specimen were carried out.

1. Introduction

The increase of mechanical properties is a major objective in material science. Important contributions in this context have been brought in recent decades by the development of so-called "top-down" techniques. Known as severe plastic deformation (SPD) [1], these techniques realize grain refinement by repetitive processes, where the initial cross-section dimensions of the specimen remain unchanged at the end of processing cycles. Very high strain is achieved after several cycles and the grain is fragmented to ultrafine or nanometric size. According to the Hall–Petch relationship, the strength of the metallic materials increases with the decrease of the average grain size, so the grain refinement is usually used to improve the mechanical properties of metallic materials. When the grain reaches ultrafine size ($100\ \text{nm} < d < 1\ \mu\text{m}$), extremely high tensile and yield strength combined with a satisfactory ductility are obtained. Grain refinement by SPD implies the creation of new small grains with high angle grain boundaries (HAGBs). Generally, to obtain submicron grains with HAGBs an ultra-high effective (von Mises) strain is required ($\varepsilon_{vM} \geq 7$) [2]. By conventional deforming processes (rolling, extrusion, and drawing) only medium or high strain can be achieved (ε_{vM}=4–5).

Microstructure and mechanical behaviors of ultrafine grained (UFG) materials have attracted enormous interest of researchers from all over the world. Processes like equal channel angular pressing (ECAP) [3,4], cyclic extrusion-compression (CEC) [5], high pressure torsion (HPT) [6,7], accumulative roll-bonding (ARB) [8], repetitive corrugation straightening (RCS) [9] and multi-axial compression/forging (MAC/F) [10] were investigated and performed to obtain UFG materials.

New ideas for grain refinement, using the principle of already "classical" ECAP process, have been reported in the last years: ECAP-conform [11], incremental ECAP (I-ECAP) and double-billet incremental ECAP [12] and non-ECAP (NECAP) [13] are some of the variants that were investigated in order to make ECAP more attractive for industrial applications.

The extrusion process has a large potential for grain refinement, so the conventional direct extrusion with high ratio in one/two steps [14,15] and hydrostatic extrusion with extra-high ratio [16] were studied. Multiple direct extrusion (MDE) was earlier proposed [17,18] as a new technique in grain refinement. A repetitive indirect extrusion technique, known as accumulative back extrusion (ABE), was described recently [19,20].

In this study, a new SPD method for grain refinement of bulk materials, named repetitive extrusion and upsetting (REU) [21], consisting of successive cycles of conventional direct extrusion followed by upsetting is proposed. The description of this novel ultra-high straining process emphasizing the effective (von Mises) strain/cycle, the mechanism of grain fragmentation and the results of the experiments performed to evaluate the potential for grain refinement and mechanical properties improvement are presented.

2. Principle of repetitive extrusion and upsetting

The process begins by extruding a bar in order to elongate the initial grains. Since in the deforming zone remains a non-extruded

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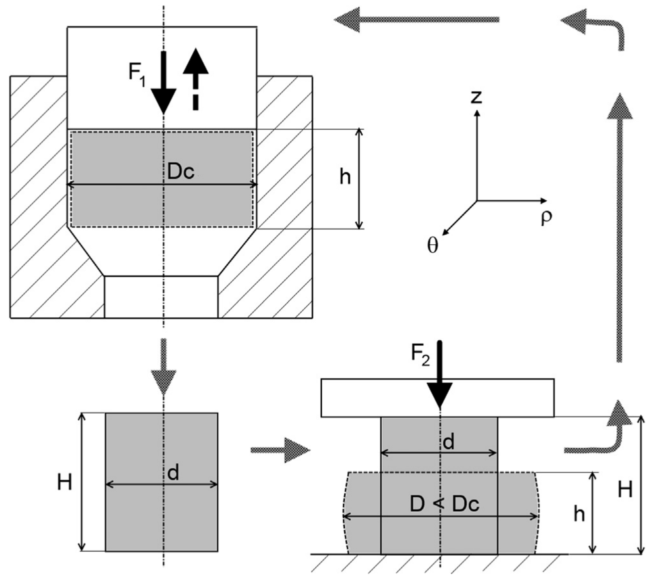

Fig. 1. Schematic representation of the REU process.

part, a second bar is inserted into the container to remove it. After complete extrusion, the first bar is upset until the initial diameter is reached again, so the extrusion process can be repeated (Fig. 1).

The dimensions of the extruded bar must fulfill the condition $H/d \leq \psi_a$, where $\psi_a \leq 2.3$ [22] to prevent buckling during upsetting. From this condition and constancy of volume, we obtain the initial height of the billet

$$h \leq \frac{d^3 \psi_a}{D^2} \tag{1}$$

where D, d and h are explained in Fig. 1.

On the other hand, the height of the bar h must be large enough to allow obtaining the diameter D again. According to the volume law

$$h \geq \left(\frac{d}{D}\right)^2 H \tag{2}$$

For limiting conditions Eqs. (1) and (2) give the exact solution for h.

REU has several advantages compared with other SPD processes: a higher strain per cycle, more shear planes with different orientations (both in extrusion and in upsetting) and consequently a more effective grain fragmentation, and no additional machining of the specimens is required. Moreover, in order to increase the workability of difficult-to-work materials, heating below their recrystallization temperature can be easily applied before upsetting. Finally note that REU consists in the combination of two well-known conventional plastic deformation processes without using any additional tools and/or devices.

3. Strain evaluation

Generally to evaluate the strain, the effective (von Mises) strain is involved

$$\varepsilon_{vM} = \sqrt{\tfrac{2}{3}(\varepsilon_\rho^2 + \varepsilon_\theta^2 + \varepsilon_z^2)} \tag{3}$$

where ε_ρ, ε_θ, ε_z, are true strains in cylindrical coordinates. For the extrusion of the cylindrical bars, $\varepsilon_\rho = \varepsilon_\theta = \ln(D/d)$ and from constancy of volume it results in $\varepsilon_z = 2\ln(D/d)$, so $\varepsilon_{vM(extr)} = 2\ln(D/d)$. Similarly, for the upsetting process $\varepsilon_{vM(ups)} = 2\ln(D/d)$.

The effective strain/cycle is given as a sum of strain in extrusion and upsetting

$$\varepsilon_{vM}/\text{cycle} = 4\ln\frac{D}{d} \tag{4}$$

For n cycles the accumulated strain is

$$\varepsilon_{vM} = 4n\ln\frac{D}{d} \tag{5}$$

To demonstrate the efficiency of REU technique for obtaining ultra-high strain let's consider an example for extrusion ratio $D/d = 2$ (engineering strain = 75%). Using Eq. (5) it results $\varepsilon_{vM} = 2.8$/cycle. In this case to achieve submicron grain only 3 cycles are necessary to fulfill the above condition $\varepsilon_{vM} \geq 7$. Note that among all SPD processes the extrusion combined with upsetting actually achieves the highest effective strain per cycle.

4. Mechanism of grain fragmentation

The grain fragmentation mechanism during REU can be explained by the velocity discontinuities (which are often used to simplify the flow model in extrusion) and by the slip line field in upsetting process. The velocity discontinuities give rise to tangential stress (τ) which can produce the bending or shearing of grains/subgrains. Along the slip lines the tangential stress reaches its maximum values, i.e. yield strength in pure shear (k).

4.1. Grain fragmentation during extrusion

Numerous studies have been focused on the analysis of axisymmetric extrusion of a cylindrical bar involving approximation and simplifying hypothesis, but the exact solutions cannot be found. Avitzur [23] and other researchers developed models for axisymmetric flow through conical converging dies using spherical, trapezoidal, triangular and toroidal velocity field. The spherical velocity field is widely accepted, so this model will be used to explain the appearance of velocity discontinuities during the passing of material through a conical converging die in direct extrusion process.

Let's consider a workpiece into a direct extrusion die. The characteristic regions and kinematically admissible velocity field are schematically presented in Fig. 2.

The workpiece can be divided in four regions (Fig. 2a). In zones I and III the velocities v_o and v_f are constant and parallel to the axis of symmetry. Due to constancy of volume $v_f = v_o(D/d)^2$. Zone II is the deforming zone where the velocity vector of any material point is oriented toward the virtual apex O. Zone IV, known as a dead metal zone (DMZ), appears only if the angle α is larger than the critical cone angle.

A kinematically admissible spherical velocity field associated with die geometry and characteristic zones in direct extrusion through conical converging die is presented in Fig. 2b. The surfaces Γ_1 and Γ_2 are spherical boundaries which separate zones I and II, and zones II and III, respectively. When a material point from zone I reaches the surface Γ_1 it undergoes a drastic change of its moving direction and starts to move toward the apex O. Inside the deforming zone II it moves along a radial line and its velocity increases ($v_o \cos\theta \leq v \leq v_f \cos\theta$) until it reaches Γ_2 where again it undergoes a sudden change of direction, moving parallel to the axis of symmetry. Note that a material point on the surface moves slower than a material point from the center of the rod and consequently the grains inside the area near the die surface are elongated. If zone IV is formed, the surface Γ_3 acts as an interface between two velocity fields: one continuous and the other stationary (dead zone), so velocity discontinuities occur along it.