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Single-pass severe plastic forming of ultrafine-grained plain carbon steel

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Abstract

We developed an extrusion process with a cross-sectional area reduction as ‘single-pass severe plastic forming (S^2PF)’ process for producing ultrafine-grained plain carbon steels. We investigated the microstructure and mechanical properties of fine-grained 0.2% carbon steels extruded at 1100–600 °C. Ultrafine ferrite grains with a grain size of 1.2 μm were generated at the surface of the materials extruded at 700 °C. The materials extruded at 800, 700 and 600 °C were investigated by scanning electron microscopy, electron backscattering diffraction analyses, tensile tests and compression tests. Extrusion at 700 °C, which is near the austenite–ferrite transformation temperature (A_{r3}), produced a material sample with a diameter of 5 mm, an average ferrite grain size of approximately 2 μm, a tensile strength of about 700 MPa, a uniform elongation of about 15% and a good cold-forging property.

Keywords: Extrusion; Single-pass severe plastic forming (S^2PF); Plain carbon steel; Transformation temperature; Recrystallization; Ferrite grain size

1. Introduction

Fine microstructures lead to superior mechanical properties of a bulk material. To generate steels with ultrafine grains (UFGs), severe plastic deformation (SPD) and advanced thermomechanical processes (ATPs) are known as efficient methods [1]. SPD processes such as ECAP (equal channel angular pressing) [2–4] and ARB (accumulative roll-bonding) [5], and ATPs such as hot deformation with controlled cooling [6–8] or warm deformation [9,10] have been developed and reported. The SPD techniques, which impose a large strain (e.g., a total true strain of above 3), are only useful for producing laboratory-scale samples because of their accumulative characteristics, and the finished grains are elongated in many cases. On the other hand, large-scale industrial steels with UFGs can be efficiently produced by ATP techniques. High-speed hot deformation followed by controlled cooling with austenite dynamic recrystallization is an approach for obtaining equiaxed random microstructures. Warm rolling is also a continuous process, resulting in equiaxed ferrite grains.

It was found that extrusion with cross-sectional area reduction [11,12] could realize SPD for the generation of UFGs in a single pass, and austenite static recrystallization could be suppressed by cooling immediately after hot extrusion. The advantages are not only the single-pass hot SPD but also the flexibility of the finished shape of the cross-section, relatively compact equipment and low consumption of energy. Furthermore, various ferrite grain sizes can be generated by changing the extrusion temperature or cooling rate, as in industrial hot forming.

In this study, we have developed a new potential method of extrusion with a cross-sectional area reduction, we named ‘single-pass severe plastic forming (S^2PF)’, for producing ultrafine-grained steels. Mild steels (0.2% carbon) are processed by S^2PF at hot and warm phases (1100–600 °C). The microstructures of the materials extruded at 800/700/600 °C are observed by field-emission scanning electron microscopy (FE-SEM), and the distributions of misorientation angles and textures are clarified by electron backscattering diffraction (EBSD) analyses. The mechanical properties of the extruded bulk materials are examined by tensile tests at room temperature and cold compression tests.

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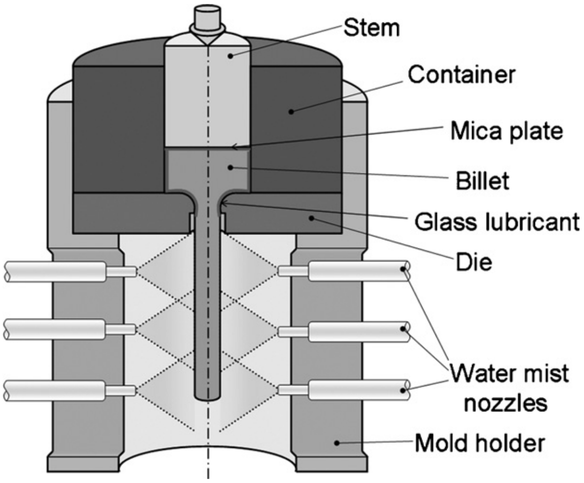

Fig. 1. Cross-section of extrusion setup.

2. Extrusion experiment

Fig. 1 shows the configuration of the extrusion setup. We adopted forward extrusion. The die had an R-shaped longitudinal section and a round cross-section. The container also had a round cross-section that was concentric with the die. Ferrite–pearlite plain carbon steel, S20C (Fe–0.21C–0.47Mn–0.17Si–0.16P–0.14S, wt.%), was used as the billet material. The mean ferrite grain size of the billet was approximately 17 μm. The cooling system was capable of water mist cooling with a controllable cooling rate. The water mist nozzles were set immediately below the die. Three nozzles in the extrusion direction were arranged in four directions around the extruded billet for uniform cooling.

The extrusion ratio (i.e., cross-sectional area reduction) ρ is expressed by $\rho = A_0/A_1$, where the cross-sectional area before extrusion is represented by A_0 and that after extrusion is A_1. The average strain imposed after extrusion $\bar{\varepsilon}$ is expressed by

$$\bar{\varepsilon} = \ln \rho. \tag{1}$$

The internal diameter of the container was 22 mm and those of two types of die were 10 and 6.5 mm, i.e., the extrusion ratios were $\rho = 5$ and 12, respectively. The average strains were $\bar{\varepsilon} = 1.6$ and 2.4, and these corresponded to rolling reductions r of 75% and 88%, respectively. Note that the surface regions of the extruded products are subjected to greater strain because of shear deformation by friction [13,14]. The dies were machined to R7 mm in the longitudinal section. The extrusion speed was 9 mm/s; therefore, the average strain rates without the consideration of dead metal were $\dot{\bar{\varepsilon}} = 2.1\ \mathrm{s}^{-1}$ when $\rho = 5$, and $\dot{\bar{\varepsilon}} = 3.1\ \mathrm{s}^{-1}$ when $\rho = 12$. Hot-working-tool steel, SKD61 (JIS, $H_{RC} > 53$), was used as the material for the stem, container and dies. A mica plate was inserted between the stem and the billet for heat insulation. Glass lubricants [12,15,16] were applied around and at the bottom of the billets. The chemical compositions of the glass lubricants are shown in Table 1. Two kinds of lubricants with moderate viscosities at high temperatures (≥1000 °C) and at low temperatures (≤900 °C) [16] were selected. The diameter of the billets was 20 mm and the height was 40 mm. The billets were heated to 1000 °C and kept at this temperature for 5 min before extrusion when the extrusion temperature was less than 900 °C. This process was carried out to completely transform the microstructure into austenite grains. The temperatures of the billets immediately before extrusion were directly measured using a K-type thermocouple inserted into the center of each billet. The natural cooling rate in the mold was about 2 °C/s. The cooling rates without deformation due to water mist cooling were 35 °C/s when the diameter was 10 mm, and 50 °C/s when the diameter was 6.5 mm.

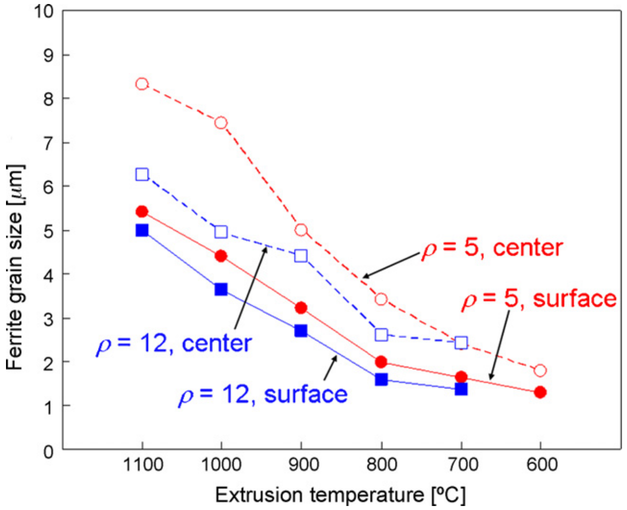

Fig. 2. Ferrite grain sizes at the center and surface (100 μm below the edge) of extruded materials.

3. Results and discussion

3.1. Grain sizes and SEM observation of fine-grained microstructures

Fig. 2 shows ferrite grain sizes at the surface region (100 μm below the edge) and the center region of the materials extruded at the extrusion temperatures of 1100/1000/900/800/700/600 °C and the extrusion ratios of $\rho = 5$ and 12. The ferrite grain sizes of the materials extruded at more than 900 °C (diameter > 3 μm) were measured by optical microscope observation, and those of the materials extruded at 800, 700 and 600 °C were measured by FE-SEM observation. Finer ferrite grains were generated at

Table 1
Viscosities and chemical compositions of glass lubricants (wt.%) (A: 1100–1000 °C extrusion, B: 900–600 °C extrusion [17])

	Viscosity	SiO_2	Al_2O_3	B_2O_3	Na_2O	K_2O	CaO	MgO
A	200 Pa s at 1150 °C	56	15	6	0.5	0.2	22	0.6
B	130 Pa s at 800 °C	33	2	36	16	1	8	4