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Control of ultrafine microstructure by single-pass heavy deformation and cold forging of metal

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ABSTRACT

A hot extrusion system with controlled cooling is investigated in this study. This system is used with the aim of manufacturing steel and other metal products with ultrafine microstructures by single-pass heavy deformation followed by controlled cooling. The continuous formation of bulk materials with the desired geometry and microstructure could be realized using the proposed system or by adding hot rolling stands after processing using the proposed system. Microstructure evolution during and after heavy single-pass deformation is examined through a series of experiments involving the hot extrusion of plain carbon steel followed by controlled cooling. The effects of severe plastic deformation on grain refinement and the mechanical properties of the formed products are discussed. It is clear that the use of the proposed system is helpful for the grain refinement of a cast microstructure. Also, ultrafine-grain steel with a grain diameter of 3 μm can be formed using the proposed system. Finally, the formability of the ultrafine-grain steel manufactured using the proposed system is examined by a cold-forging experiment.

1. Introduction

Metal forming should be capable of adding three functions to the products formed: better geometrical precision, better surface quality and better mechanical properties products. Novel designs of the forming sequence should simultaneously optimize these three functions, because they are closely related to the additional value of the formed product. In fact, the increasing demand for the simultaneous generation of the geometry and the surface in cold forging, and the simultaneous generation of the geometry and microstructure in hot forming, can be observed in metal-forming research in the last decade.

Hot forming enables the control of the microstructure of the formed product by controlling and utilizing the metallurgical behavior of the metal in an appropriate manner. The mechanical properties of a formed product are strongly dependent on the final microstructure that evolves through recrystallization, recovery and transformation during hot forming. For example, the strength of a hot-formed product σ^{TS} is governed by the grain size d, as given by the Hall–Petch relation $\sigma^{TS} \propto 1/\sqrt{d}$. Also, the ductile–brittle transformation temperature (DBTT) depends on the grain size d, DBTT $\propto -1/\sqrt{d}$. Since, controlled rolling is widely used to manufacture plates, sheets and rods with fine ferrite grains (Sellars and

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Beynon, 1992), increasing demand for eliminating the annealing process is promoting the controlled forging of microalloyed steels (Ishikawa et al., 2000) and highly alloyed steels (Shen et al., 1993). The microstructural analyses of hot forging and hot rolling have attracted the attention of many researchers, because it provides a basic analytical scheme for the simultaneous optimization of the geometry and microstructure of hot-formed products (Maccagno et al., 1996; Karhausen and Kopp, 1992).

To manufacture steels and other metals with finer grains, hot forming at a low temperature with high reduction and forming speeds is suitable (Torizuka et al., 2000), because the high residual dislocation density attained under such forming conditions is helpful for promoting accelerated static recrystallization into finer grains. In addition, the accelerated transformation from a microstructure with a high dislocation density is also helpful for promoting the additional grain refinement of ferrous steels, which leads to a higher value of σ^{TS} and a lower DBTT without sacrificing the formability of the products. Consequently, a high residual dislocation density is the key target for the optimization of hot-forming conditions. In fact, tandem hot strip rolling with reduced heavy thickness at a low temperature is now being used to manufacture steel sheets with finer grains (Yanagimoto et al., 2002). However, the residual dislocation density of a sheet after tandem hot sheet rolling is always lower than that of the sheet after total thickness reduction. This is due to the rapid recovery of dislocations between the rolling stands at elevated temperatures (Yada et al., 1983). Therefore, to promote the refinement of the grains and microstructure, heavy single-pass deformation is more effective. It can also be induced in any type of steel or other metal by glass-lubricated hot extrusion (Sejournet and Delcroix, 1955). The plastic flow of metals during extrusion is in the stress field under pure compression from all directions; thus, the extrusion of steels and metals is possible even though the metal has poor workability.

The microstructure evolution in heavy single-pass deformation by glass-lubricated hot extrusion is investigated in this study. A series of hot extrusion experiments on plain carbon steel with accelerated cooling are conducted to elucidate the effects of the hot-extrusion and cooling conditions on the microstructure of the formed products. The effects of these conditions on the strength and elongation are evaluated by tensile tests. Finally, the cold formability of the extruded products is examined by cold-forging tests under severe plastic deformation.

2. Experimental procedure

A schematic illustration of the experimental setup is shown in Fig. 1. A hydraulic press with a maximum pressing force of 1000 kN is used in a hot extrusion experiment on a steel billet.

The plastic strain $\bar{\varepsilon}$ imposed on materials subjected to extrusion is expressed by the following equation:

$$\bar{\varepsilon} = \ln \rho \qquad (1)$$

Redundant deformation such as shear deformation is neglected in Eq. (1). It may be due to the imposed plastic strain after extrusion is always greater than that expressed by Eq. (1). Under the same assumption, the plastic strain after rolling is expressed by Eq. (2).

$$\bar{\varepsilon} = \frac{2}{\sqrt{3}} \ln(1 - r) \qquad (2)$$

Here, r is the thickness reduction after single-pass rolling. The relationship between the extrusion ratio ρ and the thickness reduction r is shown in Fig. 2. From this figure, the maximum extrusion ratio used in the present investigation, $\rho = 11.6$, is found to correspond to the rolling reduction $r = 0.88$ (88%), which is impossible to obtain by single-pass rolling. In contrast, an extrusion ratio of approximately 10 can be easily attained by the glass-lubricated extrusion of steels and other metals. The plastic strain $\bar{\varepsilon}$ imposed on steels with the extrusion ratio $\rho = 11.6$ is about $\bar{\varepsilon} = 2.5$, although this can be applied by single-pass deformation during continuous hot forming. This plastic deformation corresponds to the total strain induced by the multipass rolling of a sheet to reduce the thickness from 25 mm to 3 mm, which is the normal rolling

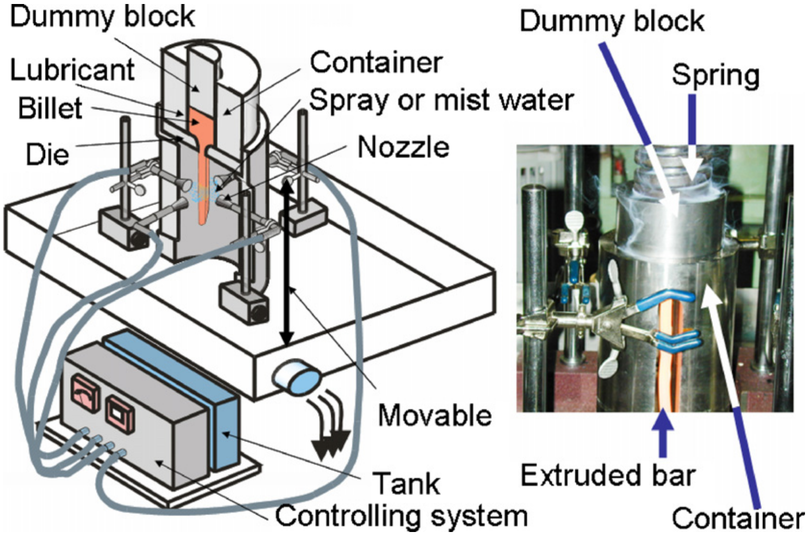

Fig. 1 – Schematic of experimental procedure.