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Finite-element analysis of severe plastic deformation in differential-speed rolling

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ABSTRACT

Differential-speed rolling can impose severe plastic deformation on a metallic sheet by developing extensive shear strain. Plastic deformation by a single pass with a speed ratio of 3 was found to be as high as 3.5 in terms of the effective strain. Although the speed ratio, the friction coefficient and the length of deformation zone are important parameters in controlling the differential-speed rolling, their effects on plastic deformation are yet unknown. In the present study, these effects were investigated by the rigid-plastic finite-element analysis, and as a result logics in dissipation of power, mechanisms in development of plastic deformation and an upper limit of the speed ratio were found. Moreover, a double-pass differential-speed rolling was introduced to achieve a symmetric distribution of the effective strain through thickness of a sheet. An excessive speed ratio would waste unnecessarily a portion of the power through friction at the interface between the sheet and rolls, and also exert a tensile stress in the sheet, which could result in fracture if the material of the sheet is as brittle as a magnesium alloy.

1. Introduction

DSR (differential-speed rolling), where two rolls rotate with different speeds, can impose more plastic deformation than conventional rolling or ESR (Equal-Speed Rolling) can. It has thus been applied to refining grains and controlling textures in various metallic sheets, as discussed in the following studies. Compaction of electrolytic Cu powder was performed by DSR and the relative density of the powder strip became 15% greater than that by a conventional rolling under the same rolling load [1]. Mg–AZ31 sheets were processed by DSR with a speed ratio of 1.1 at 200 °C and as a result a higher ductility was obtained due to the basal plane orientation inclined by 8° from the normal direction toward the rolling direction with accompanying a grain refinement [2]. The material was further processed by DSR with a speed ratio of 3 and very fine equiaxed grains were obtained [3]. Shear strain was found to attribute to as much as 60% of the total effective strain of 3.5. Grains however would be at a risk of growth due to an increase in temperature as much as 90 °C by plastic deformation and friction, if the initial temperature of the sheet was set high improperly [4]. A more homogeneous microstructure with a weaker basal texture at mid-layer in Mg–AZ31 sheets was obtained with increasing reduction per pass in DSR [5]. Deformation as well as shear bands were dominant in Mg–AZ31 sheets at a low speed ratio and microstructures were dynamically recrystallized at a high speed ratio due to an increase in temperature [6]. DSR was also applied to other materials, such as pure Ti sheets [7]. As the rolling temperature was higher than 573 K, a larger Lankford value with a smaller planar anisotropy was obtained in spite of a decrease in tensile elongation. Ferrite grains in IF steel were reduced from 35 μm to 0.7 μm through 4 passes of DSR, which was equivalent to the effective strain of 1.7 [8]. As a multi-pass DSR was applied to Al-5052 sheets, equiaxed grains of 0.7 μm were obtained due to the fact that, by a sample rotation of 180° along the longitudinal axis, the band-like shear deformation formed in a previous pass was intersected by that of the following pass [9].

Although relations between plastic deformation and process parameters, such as speed ratio, friction coefficient and length of deformation zone were critical for a proper control of DSR, they have been yet unknown. In the present study, these relations were to be found by using DEFORM, that was based on the rigid-plastic finite-element method. During the course of the study, the effective-strain distribution through sheet thickness developed by DSR was found to be asymmetric, which would result in asymmetric distributions of microstructure and physical properties at a later stage. Thus, a double-pass DSR was introduced to improve the distribution to be symmetric by reversing the roll speeds in the second pass.

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2. Fundamentals of DSR

Schematic of DSR is illustrated in Fig. 1, where two rolls of 300 mm in diameter rotate in opposite directions with a speed ratio of 3 and a sheet passes through the gap between the rolls. The speed ratio was defined by a ratio obtained by the fast-roll speed divided by the slow-roll speed. The sheet deforms mostly in the deformation zone between the entrance and the exit, where the initial thickness t_o is reduced to the final thickness t_f, as shown in Fig. 2. Tangential speeds of the upper and lower rolls are designated by V_{ur} and V_{lr}, respectively, and those of the upper and lower surfaces of the sheet are V_{us} and V_{ls}, respectively.

2.1. Dissipation of power

In ESR, V_{ur} equals V_{lr}, and V_{us} equals V_{ls}. The neutral points in the upper and lower contact surfaces are at the same location in the direction of rolling. If pressure P or the shear strength k is known at the contact surface, the frictional stress can be expressed as μP in the Coulomb friction or mk in the constant shear friction. Here, μ is the Coulomb friction coefficient and m is the shear friction factor. In DSR, as shown in Fig. 3, V_{ur} is greater than V_{lr}, and V_{us} is greater than V_{ls}. The neutral point in the upper contact surface is located near the exit while the other in the lower contact surface is near the entrance. The power provided by the upper roll is represented by the area of a-e-e'-d-a minus the area of e-b-c-e'-e multiplied by the frictional stress, while that by the lower roll is the area of a''-f-f'-d-a' minus the area of f-b'-c-f'-f multiplied by the frictional stress. The power used for deformation by the upper roll is the areas of a'-g-e-e'-d-a' minus the area of e-b-c-e'-e multiplied by the frictional stress, while that by the lower roll is the area of a'-f-f'-d-a' minus the area of f-g'-b-c-f'-f multiplied by the frictional stress. The power wasted by friction is the power provided by rolls minus the power used for deformation. Especially, the power used for shear deformation due to the differential speed is represented by the area of a'-g-b-g'-a' multiplied by the frictional stress.

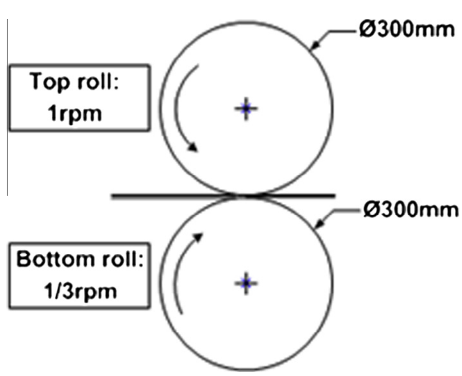

Fig. 1. Schematic illustration of DSR (speed ratio = 3).

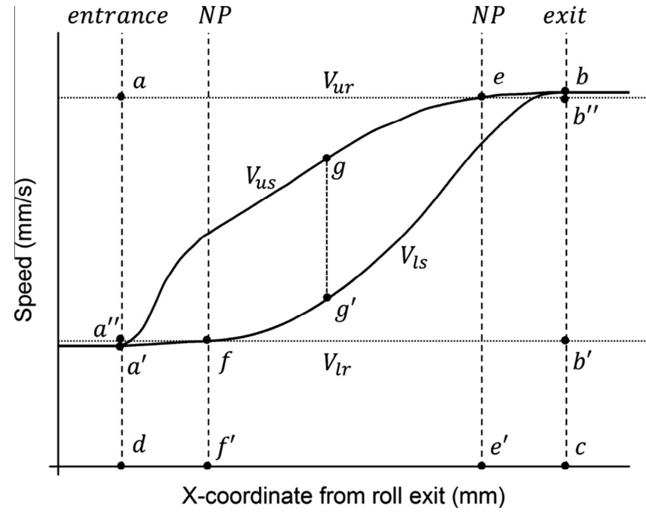

Fig. 3. Speed profiles in deformation zone in DSR.

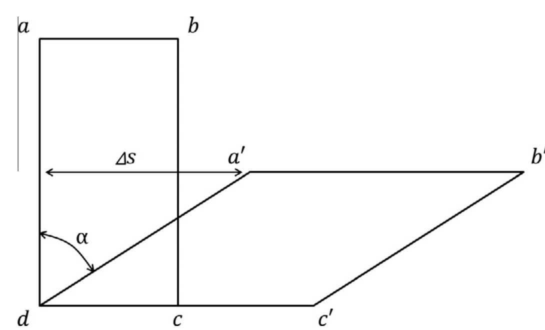

Fig. 4. Simplification of plastic deformation in DSR.

2.2. Development of plastic deformation

Plastic deformation in DSR consists of compression and shear deformation. It can be simplified as deformation from a rectangle to a parallelogram, as shown in Fig. 4. As the shear distance Δs or the shear angle α increases, shear strain γ increases in magnitude. Since Δs cannot be greater than L, the length of deformation zone, a relation in Eq. (1) was derived to approximate the magnitude of shear strain. Here, Δt stands for the time required for a material point on the fast surface of the sheet to pass through the deformation zone, t_{ave} stands for the average thickness of the sheet, $\Delta t'$ stands for the time required for a material point on the surface of the fast roll to pass through the deformation zone, C varies from 0 to 0.7 and C' varies from 0 and 0.5. As the speed ratio, the friction coefficient or the length of deformation zone increases, ε_{xy} increases in magnitude and thus values of C and C' increase accordingly.

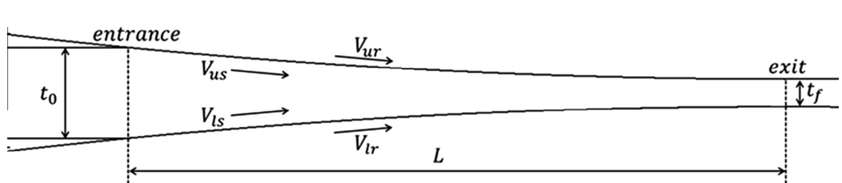

Fig. 2. Schematic illustration of deformation zone in plane-strain rolling.