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Influence of roll radius on contact condition and material deformation in skin-pass rolling of steel strip

Hideo Kijima*

Rolling and Processing Research Department, JFE Steel Corporation, 1, Kokan-cho, Fukuyama, Hiroshima, Japan

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ABSTRACT

Skin-pass rolling (or temper rolling) is the final forming step in the production of cold rolled steel sheets. Although a large roll radius compared to the contact length is one of the characteristics of skin-pass rolling conditions, numerous studies have been conducted thus far using laboratory mills with small radius rolls. In this paper, the influence of roll radius on the contact condition and material deformation in skin-pass rolling is examined and clarified by numerical analysis by an elastic–plastic FEM analysis as well as experimental rolling tests, which were performed to verify the result of the analysis. Some characteristics of skin-pass rolling related to pressure distribution, contact condition and material deformation are not properly simulated using small radius rolls. Considering characteristic skin-pass rolling conditions, two cases using simplified models, i.e., vertical compression and rolling with a circular, rigid roll, were analyzed.

1. Introduction

Skin-pass rolling (or temper rolling), usually following the annealing process, is the final operational step in the production of cold rolled steel sheets, and has a great influence on mechanical properties including Lüderband prevention, surface topography, strip flatness and so on. The parameter settings in skin-pass rolling are quite different from those in conventional plate rolling due to the small reduction (app. 1%), large contact length compared to the sheet thickness, large roll radius compared to the contact length and high friction. Considering those conditions, it is expected that material deformation will not be uniform in the through-thickness direction, and the influence of the elastic deformation of the rolls on material deformation will be crucial.

Most of the early literatures on theoretical/numerical modeling of skin-pass rolling simplified either the inhomogeneous material deformation or the elastic deformation of the rolls. In the former approach, the slab method combining precise, non-circular elastic analysis of work roll deformation (Jortner et al., 1960) was used to calculate the rolling force for certain conditions. Fleck et al. (1992) developed a realistic model to describe an aluminum foil rolling process which includes a long flat region where the strip thickness does not change. Their model had been used to develop models of skin-pass rolling. Krimpelstätter et al. (2004) utilized a regularized Coulomb friction law to express a sliding region and a sticking region (a no-slip-zone). The thickness distribution inside the roll gap is similar to the results from FE simulation mentioned later, qualitatively. Domanti et al. (1994) analyzed a wet skin-pass rolling condition, in which the friction coefficient was modeled as around 0.05, with the foil rolling model. They showed the same thickness distribution pattern in wet skin-pass rolling as in foil rolling. Matsumoto and Shiraishi (2008) separately calculated a skin-pass rolling condition with the long flat region, and proposed a model to stabilize the convergence calculation which allows elastic deformation of the strip in the flat region. All those studies focused on and succeeded in practical rolling force calculations, respectively, by considering the non-circular deformation of the work roll, whereas the mechanism of the material deformation was not clarified.

In the latter approach, the rolls were modeled as circular and rigid with a flattened radius, and inhomogeneous, elastic–plastic deformations of the material were analyzed by FE model. Yarita and Itoh (2008) compared the calculated rolling load with the slab method and concluded that the both results showed good agreement under a small friction and small roll condition. Kijima and Bay (2006, 2007) showed that the skin-pass rolling process can be modeled as plane strain upsetting of a sheet strip with long narrow tools and clarified the basic mechanism of inhomogeneous material deformation and the contact condition for the case of high friction and smooth tool surfaces.

Although a large roll radius compared to the contact length is one of the characteristics of skin-pass rolling, numerous studies have been conducted thus far using laboratory mills with small radius rolls, mainly in order to investigate roughness transfer from the rolls to the material. Kimura et al. (2009) showed that the large

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* Tel.: +81 84 945 4162; fax: +81 84 945 3840.
E-mail address: h-kijima@jfe-steel.co.jp

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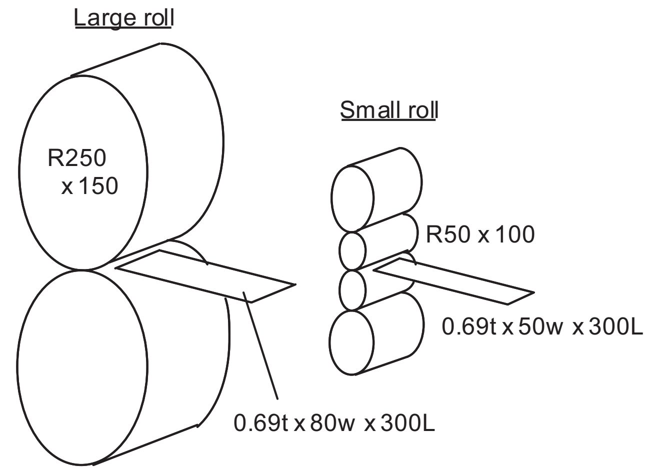

Fig. 1. Laboratory rolling mills.

roll could enlarge the roughness transfer for the same elongation. Nevertheless, the influence of roll radius on roughness transfer has not been discussed in relation to the mechanism of material deformation in the literature.

Recently, some papers have shown that skin-pass rolling conditions can be successfully analyzed by commercial FE analysis programs, even combining elastic–plastic deformation of the material and elastic deformation of the roll. Sun et al. (2009) numerically showed the effects of elongation, friction coefficient, yield stress and entry/delivery tension on the pressure and shear stress distributions and elastic roll deformation patterns. As a result, they concluded that any factor that increases the rolling load may lead to elongation of the central flat region, but they did not discuss the mechanism of material deformation. Akashi et al. (2008) investigated the jumping phenomenon in wet skin-pass rolling with a bright work roll (Imai et al., 1980) and proposed a mechanism for its occurrence in relation to the friction coefficient.

In the present paper, the influence of roll radius on the contact condition and material deformation is investigated numerically and experimentally in rolling of relatively soft, medium-to-heavy gauge steel strip with relatively smooth rolls, as a basis for clarifying the influence of roll radius on roughness transfer, for which the author plans to report an experimental investigation in future. Here, the same material, namely, an annealed carbon steel strip, is rolled using two laboratory mills with different work roll radii. A numerical analysis, combining elastic–plastic deformation of the material and elastic deformation of the roll, is conducted to simulate the experimental conditions using commercial FE software. The appropriateness of two simplified models, i.e., simple compression with elastic roll and skin-pass rolling with a rigid circular roll, is also discussed.

2. Experimental apparatus and FEM analysis

2.1. Experimental conditions

Experiments were carried out with two laboratory mills. As shown in Fig. 1, one was a 2Hi mill with a work roll radius of 250 mm as an example of the operational size (hereinafter referred to as “large roll”) and a 150 mm barrel width. The other was a 4Hi mill with a work roll radius of 50 mm as an example of the laboratory size (hereinafter referred to as “small roll”) and 100 mm barrel width. The roll material is high chromium steel, SUJ2 as provided in JIS G 4805 (similar to AISI E52100), which was hardened and tempered to HRC 65. The roll surface was ground to 0.2 μm Ra.

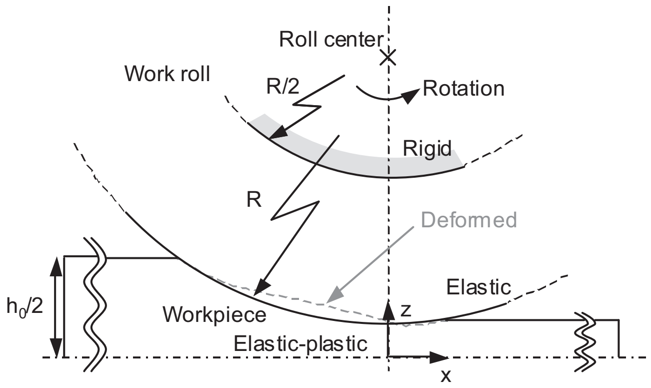

Fig. 2. Schematic outline of skin-pass rolling model.

The workpiece is an annealed low carbon steel strip of which discontinuous yield behavior is practically negligible in order to ease FEM calculations to obtain convergence. Its mechanical properties were modeled as described in the next section. The dimensions of the workpiece strips were thickness, h_0, 0.69 mm, length, 300 mm and width, 80 mm and 50 mm, respectively for the large and small rolls.

Before rolling, the roll and workpiece surfaces were both carefully degreased with petroleum benzin to achieve dry friction conditions.

In order to measure elongation, the workpiece surface was marked with two scratched lines in the cross-width direction, with a spacing of 150 mm in the longitudinal direction. The distance in the longitudinal direction was measured before and after the experiment with a microscope equipped with a micrometer device.

The rolling velocity was 5 m per minute.

2.2. Conditions in FEM analysis

The FEM analysis simulating the experiments described above was carried out by the two-dimensional, plane strain, static implicit method in Abaqus standard ver.6 to predict the contact condition and the deformation pattern. Fig. 2 shows a schematic outline of the model. The upper half of the roll and the workpiece were modeled considering the symmetry around the horizontal center line in the workpiece thickness.

The central part of the roll corresponding to the half radius was modeled as rigid to stabilize the analysis and to shorten the simulation time. The workpiece length in the FEM model was decided to be more than 10 times the expected contact length which was determined by preliminary analyses with a shorter model length. Loading was modeled by applying a certain vertical downward displacement of the roll on the front tip of the workpiece in the first step. Thereafter, the roll was rotated around its center, which was considered to be fixed at the position of displacement.

The roll was modeled as an elastic body with Young’s modulus $E = 205.8$ GPa and Poisson’s ratio $\nu = 0.3$. The workpiece was assumed to be elastic–plastic with Young’s modulus $E = 205.8$ GPa, Poisson’s ratio $\nu = 0.3$ and initial yield stress $\sigma_0 = 165.8$ MPa. Work hardening was determined by connecting the dotted points on the tensile test of the workpiece used in the experiment as shown in Fig. 3. The Von Mises criterion was used. Adopting Coulomb’s law, a friction coefficient of 0.3 was used to simulate the dry friction condition (Kijima and Bay, 2007). The contact problem between the roll and the workpiece was solved adopting the penalty method for normal penetration as well as tangential sliding (Kijima and Bay, 2007).

The mesh for the workpiece was square and 1/16th the size of the workpiece thickness. The mesh for the contact surface region of