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Influence of roll radius on roughness transfer in skin-pass rolling of steel strip

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A R T I C L E I N F O

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A B S T R A C T

Skin-pass rolling (or temper rolling) is usually the final process in the production of cold-rolled steel sheets. One of the main objectives in skin-pass rolling is to obtain a certain surface roughness profile. Although a large roll radius compared to the contact length and the reduction in thickness 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 roughness transfer in skin-pass rolling is investigated by experimental rolling tests as well as numerical analysis by elastic–plastic FEM. A simple but useful method of estimating roughness transfer is suggested. It was found that some characteristics of skin-pass rolling related to roughened rolls are not properly simulated using small radius rolls.

1. Introduction

Skin-pass rolling (or temper rolling) is usually performed following the annealing process and is the final operational step in the production of cold-rolled steel sheets. It 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 sheet 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.

In addition to these characteristics, the surface of the work roll is roughened intentionally in some cases to achieve a certain strip roughness, because surface roughness after skin-pass rolling is one of the most important qualities of steel products. It is well known that strip roughness affects formability in press forming, including galling behavior with tools, and also affects the image clarity of painted sheets. Numerous studies have investigated the relationship between roughness parameters and the qualities mentioned above. Marique et al. (1983) investigated the relationship between roughness and the properties of cold-rolled steel sheets, and found that surface roughness should be below a certain average roughness in order to achieve high image clarity after painting, and a low-porosity phosphate layer can be obtained provided the average roughness is higher than a certain value. Hirasaka (1990) conducted experiments to investigate the effect of surface micro geometry on galling behavior with tool surfaces, and concluded that higher surface waviness is associated with longer tool life. Nishimura et al. (1991) introduced a high image clarity steel which is rolled with roughened rolls processed by laser texturing.

It is also known that roll roughness affects skin-pass rolling conditions. Masui (1976) presented operational knowledge that large elongation can be obtained with a smaller rolling force under certain skin-pass rolling conditions by using roughened rolls. Sutcliffe (1988) performed a slip line field analysis which revealed that multiple indentations can lead to larger elongation in the longitudinal direction than compression with a plane tool and showed the importance of the pitch length. Ike (2004) obtained results similar to those of Sutcliffe in his elasto-plastic FE analysis of multipunch indentation. Domanti and Edwards (1996) applied Sutcliffe's analysis to calculate the rolling forces under dry skin-pass rolling conditions, and concluded that roughened rolls decrease the specific rolling force, and the magnitude of this reduction is more significant for thinner strip thickness. Dixon and Yuen (2006) considered the effect of strip surface steepness on rolling force. Their calculations, which were based on the slab method, showed good agreement with operational data and revealed, in particular, that surface steepness is important only in the case of low elongation. Kijima and Bay (2008a,b) investigated the mechanism of larger elongation by a roughened tool in an experiment involving plane strain upsetting under small reduction and an elastic–plastic FE analysis of the experimental conditions. The results revealed a significant effect of pitch independent of the roughness value.

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Both experimental and analytical studies have attempted to elucidate the mechanism of roughness transfer to achieve a certain roughness profile. Steinhoff et al. (1995) calculated the roughness transfer from a work roll roughened by electron-beam texturing to hot-dip galvanized steel sheets, and revealed that the workpiece surface extrudes under a certain rolling condition. Deutscher (1997) investigated the change in the average roughness R_a of the rolled steel strip, as measured by three-dimensional scanning, by rolling length when using rolls roughened by shot blast texturing, electric discharge texturing and laser texturing. Shot blast texturing showed the best tool life, and the results could be explained by comparing the bearing curves. Although a large roll radius compared to the contact length is one of the characteristics of skin-pass rolling, more specific studies have been conducted thus far using laboratory mills with small radius rolls. Nagase et al. (2009) carried out an experimental study of roughness transfer under a dry skin-pass rolling condition with small rolls and evaluated roughness transfer from the bearing curves. At the typical elongation in skin-pass rolling, only the peak part of the roll surface texture can be directly transferred to form valleys on the steel product. Kimura et al. (2009) showed that use of a large roll can increase roughness transfer at 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. In particular, even though average roughness R_a is one of the most important roughness parameters in operation, the dominant operational parameter for predicting roughness transfer has not been discussed in relation to the mechanism of material deformation in skin-pass rolling. Kijima and Bay (2008a,b) simulated skin-pass rolling conditions in an experiment involving plane strain upsetting. They concluded that roughness transfer in skin-pass rolling is dominated by the peak pressure at the center of the contact region, where lateral deformation of the workpiece is constrained by high hydrostatic pressure, and relative sliding near the exit enlarges roughness transfer due to the so-called junction growth effect (MacFarlane and Tabor, 1950), even in elastic–plastic deformation.

Recent papers have presented FE analysis results for skin-pass rolling conditions, successfully using commercial programs, and have even combined elastic–plastic deformation of the material and elastic deformation of the roll. Sun et al. (2009) demonstrated numerically the effects of elongation, friction coefficient, yield stress and entry/delivery tension on 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. Kijima (2013) clarified the differences in the contact condition and material deformation behavior with different roll radii in skin-pass rolling with smooth rolls, and also pointed out the similarity between phenomena which occur in skin-pass rolling and those in vertical compression with a large roll.

In the present paper, the basic mechanism of roughness transfer in relation to material deformation is investigated experimentally and numerically in rolling of relatively soft, medium-to-heavy gauge steel strip with rough rolls, following the previous investigation with smooth rolls (Kijima, 2013). In particular, this investigation focuses on the influence of the roll radius and the important operational parameters for actual production. Here, the same material as in the previous report, namely, an annealed carbon steel strip, is rolled using two laboratory mills with roughened work rolls of different radii. A numerical analysis, combining elastic–plastic deformation of the material and elastic deformation of the roll, which is modeled as having a roughened surface, is performed with commercial FE software to simulate the experimental conditions. Additional simplified conditions, i.e., vertical compression with an elastic roll and vertical indentation of one roughness pitch are also investigated to clarify the discussion.

2. Experimental apparatus and FEM analysis

2.1. Experimental conditions

Experiments were carried out with two laboratory mills, which were the same as those used with smooth rolls in the previous paper (Kijima, 2013). With the exception of the added roll surface conditions mentioned below, the basic experimental conditions were also the same.

The roll surface was prepared in three different variants: (a) smooth: ground in the longitudinal direction to a roughness $R_a \approx 0.2\,\mu\text{m}$, which was used in the previous paper, (b) rough: roughened by electro-discharge texturing to a roughness $R_a \approx 3.1\,\mu\text{m}$, and (c) very rough: roughened by electro-discharge texturing to a roughness $R_a \approx 8.0\,\mu\text{m}$. Roll roughness was measured by a mechanical profilometer in the axial (transverse) direction of the roll. The cut-off lengths were chosen to be 0.8 mm for the smooth roll and 2.5 mm for the rough and very rough rolls. The measured length was five times the cut-off length. Typical surface profiles are shown in Fig. 1.

In the case of the large roll, a simple vertical compression test (Pawelski et al., 1993) was also conducted in the rolling mills with the rough roll. Because the pressure distribution of vertical compression was predicted to be similar to skin-pass rolling condition in the case of the large roll, obviously not to be similar in the case of the small roll (Kijima, 2013). After each compression, the surface roughness of the workpiece was measured around the center of the contact region in the same manner as with the rolled samples.

2.2. Conditions of FEM analysis

An FEM analysis simulating the experiments of skin-pass rolling and vertical compression described above was carried out to predict the contact condition, the deformation pattern and the mechanism of roughness transfer. The basic analytical conditions except the roll surface roughness model mentioned below are the same as those in the previous paper (Kijima, 2013). The two-dimensional, plane strain, implicit method in Abaqus standard ver.6 was utilized. The roll and the workpiece were modeled as elastic and elastic–plastic bodies respectively. Work hardening was determined by the tensile test of the workpiece used in the experiment. Adopting Coulomb's law, a friction coefficient of 0.3 was used to simulate the dry friction condition (Kijima and Bay, 2007).

Surface roughness was modeled as a series of circle segments (Kijima and Bay, 2008a) in the rolling direction, as shown in Fig. 2. To simulate the condition of the rough roll, Fig. 1(b), the roughness profile radius was set to $r = 0.245$ mm so that the average roughness is $3.0\,\mu\text{m}$ R_a and the pitch is $l_p = 0.15$ mm. The circumradius of the roughness profile was set to the original roll radius of the large roll and the small roll, respectively.

The mesh for the workpiece was square and 1/16th the size of the workpiece thickness, and finer square meshes were applied for the surface region so that the number of meshes corresponding to one roughness pitch, $l_p = 0.15$ mm, was 54. The mesh for the contact surface region of the roll was also square and was almost twice the size of the workpiece mesh.

An additional case was also analyzed in order to discuss the characteristics of roughness transfer in skin-pass rolling. This case was simple vertical indentation of one roughness profile of the roll surface model, as shown in Fig. 3 (Kijima and Bay, 2008a). The roll roughness profile was the same as that in the skin-pass rolling and vertical compression analyses in Fig. 2 and was modeled as rigid.