Journal of Materials Processing Technology 225 (2015) 1–8

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

An experimental investigation on the influence of lubrication on roughness transfer in skin-pass rolling of steel strip

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ARTICLE INFO

Article history:
Received 20 April 2015
Received in revised form 14 May 2015
Accepted 16 May 2015
Available online 27 May 2015

Keywords:
Skin-pass rolling
Temper rolling
Lubrication
Roll radius
Roughness

ABSTRACT

Skin-pass rolling (or temper rolling) is usually the final process in the production of cold-rolled steel sheets. In operation, skin-pass rolling is performed with roughened rolls, using a lubricant with a very low lubricating ability. However, relatively few studies in the literature have examined the effect of lubrication in skin-pass rolling. In this paper, the influence of lubrication on elongation and roughness transfer in skin-pass rolling is investigated by experimental rolling tests in which the relationship between lubrication behavior and the roll radius is clarified. As in a previous study of smooth rolls, the results with large, operational size rolls can be explained convincingly by height characterization parameters and are considered to be reasonable. It was also found that some characteristics of skin-pass rolling related to lubrication are not properly simulated using small radius, laboratory size rolls due to the insufficient contact length between the rolls and the workpiece.

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1. Introduction

Skin-pass rolling (or temper rolling) is usually the final operational step in the production of cold-rolled steel sheets, and is performed following the annealing process. It has a great influence on mechanical properties, including Lüderband prevention, surface topography and strip flatness. 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 and large roll radius compared to the contact length. As additional features of commercial skin-pass rolling, rolling is performed under a dry friction condition or by applying a skin-pass lubricant with a very low lubricating ability in order to avoid adhesion between the rolls and material, prevent rust on the material surface after rolling and cleanse the roll surface. In some cases, the surface of the work roll is also roughened intentionally, to obtain a so-called dull-finished roll, in order to achieve a certain roughness in the product steel sheet.

It is known that roughened roll surface affects skin-pass rolling conditions. Masui (1976) showed in a laboratory experiment that larger elongation can be obtained under certain conditions by roughened rolls. Sutcliffe (1988) performed a slip line field analysis and revealed that multiple indentations can lead to larger elongation than plane compression. Matsumoto (2013) also analyzed dry skin-pass rolling conditions with roughened rolls by the slab method, following his analysis of wet skin-pass rolling conditions with flat rolls (Matsumoto and Shiraishi, 2008). A varied coefficient of friction along with slip ratio between rolls and strips was applied to estimate rolling force better than a constant friction. Using FE simulation, 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.

In spite of the operational features mentioned above, relatively few studies in the literature have examined the effect of lubrication in skin-pass rolling with dull-finished rolls. Using Sutcliffe's results, Domanti and Edwards (1996) showed the thickness distribution inside the roll bite under various rolling conditions including lubricated skin-pass rolling with large, dull-finished work rolls, but did not explicitly mention the effect of lubrication. Dixon and Yuen (2006) considered surface roughness both on the workpiece and the work roll in their slab method analysis of skin-pass rolling. The calculated rolling force showed good agreement with the measured data under a specific condition and a proper friction coefficient value of 0.1. Kijima and Bay (2009) investigated the effect of lubrication and tool roughness in an experiment and FE analysis involving plane strain upsetting under small reduction to simulate the skin-pass rolling condition in terms of the ratio between contact length and reduction. The obtained effect of lubrication and roughness was quantified by the measured length of the sliding region, and it

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http://dx.doi.org/10.1016/j.jmatprotec.2015.05.023
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Table 1
Experimental materials and rolling mill.

(a) Workpiece: Annealed low carbon steel strip

	Thickness	Yielding behavior[a]	Surface roughness[b]			
			Ra	Rpk	Rk	Rvk
Material A	0.69 mm	Practically negligible	0.74 μm	0.956 μm	2.535 μm	0.782 μm
Material B	0.99 mm	Obviously observed	1.11 μm	0.773 μm	4.653 μm	0.948 μm

(b) Laboratory rolling mills

	Work roll radius	Roll material
Large roll	250 mm	SUJ2 (JIS G 4805/AISI E52100)
Small roll	50 mm	

(c) Roll surface

	Surface roughness[c]			
	Ra	Rpk	Rk	Rvk
Smooth	0.2 μm	–	–	–
Rough[d]	3.1 μm	4.507 μm	9.697 μm	3.097 μm
Very rough[d]	8.0 μm	11.033 μm	23.383 μm	7.867 μm

(d) Lubrication

	Lubricant	Viscosity at 50 °C
Dry	Degreased with petroleum benzin	–
Skin-pass rolling lubricant	Soluble organic acid amine	1 mm^2/s
Cold-rolling lubricant	Synthetic ester	19 mm^2/s

[a] The work hardening behavior was shown in Kijima, 2015.
[b] Cut-off length is 2.5 mm.
[c] Cut-off length is 2.5 mm.
[d] Roll surfaces were roughened by electro-discharge texturing.

is considered to be qualitatively reasonable that roughened tools led to a higher friction coefficient, even when using lubrication. Nagase et al. (2009) carried out an experimental study of roughness transfer under lubricated skin-pass rolling conditions with small, dull-finished work rolls and evaluated roughness transfer by the bearing curves. In the case of high-carbon steel, a water-soluble lubricant led to better roughness transfer performance than the dry friction condition at elongation of 3%, but it should be noted that 3% elongation is somewhat large as a skin-pass rolling condition. Shiraishi et al. (2012) experimentally investigated the effect of lubrication under a wide range of material conditions with large, dull-finished work rolls. The effect of lubrication could be seen when the elongation condition exceeded 1%, and higher lubrication led to a smaller rolling force and roughness transfer. Kijima (2013a) carried out an experimental and numerical study of contact condition and material deformation for skin-pass rolling in the dry condition with large rolls like those used in actual operation, and found that the pressure distribution can be approximated by the Hertzian theory. In the following paper (Kijima, 2014a), the roughness transfer was studied in that condition and it was found out that the peak pressure is the most important parameter. Akashi et al. (2015) proposed a combination of two-dimensional FE rolling analysis with three-dimensional die press analysis connected with mean stress in the rolling condition and elongation of the rolled material for surface roughness prediction under a lubricated and very thin material condition. In the previous paper (Kijima, 2015), the effect of lubrication was experimentally investigated with large, bright (or smooth, flat) work rolls, and auxiliary FEM analyses were also performed. A significant effect of lubrication on elongation was very well explained by the height characterization parameters of the linear material ratio curve, or bearing curve, which are some of the roughness parameters used in the ISO standard to express the lubrication property of the surface roughness profile, in relation to the roughness crushing ratio. Wentink et al. (2015) developed a simplified wear and imprint model of electro-discharge texturing rolls based on the bearing curve during skin-pass rolling of galvanized steel, and successfully provided topological quantification of roughness, peak counts and waviness.

In the present paper, the effect of lubrication on elongation and roughness transfer is investigated experimentally in skin-pass rolling of relatively soft, medium-to-heavy gauge steel strip with rough rolls, following the previous investigations with roughened rolls under the dry friction condition (Kijima, 2014a) and bright rolls under lubricated conditions (Kijima, 2015). The rolling conditions related to the laboratory mills, roll parameters, and properties of the lubricants and materials are the same as those in the previous investigations. In addition to average roughness, the above-mentioned height characterization parameters are also evaluated.

2. Experimental conditions

The experimental conditions, materials and laboratory rolling mills used in the experiments in this paper were the same as in the above-mentioned previous papers (Kijima, 2013a, 2014a, 2015) and are summarized in Table 1. The smooth roll and dry lubrication condition in the previous papers are also shown in the table.

In the case of the large roll, a simple vertical compression test (Pawelski et al., 1993) was also conducted, as was done previously under the dry condition (Kijima, 2014a). The surface roughness Ra of the workpiece is in fact rather rough, but is still considered to be sufficiently smooth compared with the roughness of the rough and very rough roll surfaces.

After rolling and compression, the surface roughness of the workpiece was measured by a mechanical profilometer in the axial (transverse) direction in the same manner as in the previous papers (Kijima, 2014a; 2015). The cut-off length of 2.5 mm was chosen for the rough and very rough rolls. The roughness transfer ratio,

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