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Necking condition of layers in clad sheets during rolling

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ABSTRACT

In rolling of clad sheets, layers often show periodical necking in the rolling direction. Mechanism of the plastic instability has not been understood sufficiently so that commercially available combinations of layers are limited. First, effects of rolling conditions on the necking were investigated through finite element analysis of some ideal rolling cases. Meanwhile, multi-pass cold rolling of three type of sandwich sheets was conducted to reveal necking evolutions experimentally. Based on the FE and the experimental results, a plane-strain compression model was proposed to simulate the experiments. The predictions based on change in strain energies show good agreement with the experiment.

1. Introduction

Clad sheets with structure of stacked dissimilar metal layers, are widely used in industries, for example, bimetals for temperature control, battery electrodes and electronic devices [1]. This is because they have unique combined functions and properties.

In industries, clad sheets are mostly manufactured through (a) surface treatment and stacking of layers, (b) solid-phase welding by rolling, i.e., roll bonding, (c) diffusion annealing, and (d) cold finish rolling [2]. Deformation in (d) cold finish rolling process is studied in this paper. It has been reported that layers in clad sheets often do not deform uniformly when total reduction is high. Layers may show periodical necking or fracture [3], which is a phenomenon of plastic instability. However, formation mechanism and criterion for the instability have not been understood sufficiently. Trials are still needed before industrial production and commercially available combinations of layers are limited.

Various factors affect the plastic instability. They can be divided into (a) materials conditions and (b) rolling conditions. For (a) materials conditions, number of layers, combination of materials, thicknesses of layers [4] etc. affect the phenomenon. Yield stresses and work hardening of layers also have strong effects [5]. For (b) rolling conditions, roll diameter, reduction in thickness, speed, lubrication, temperature and so on affect the phenomenon. Most of past theoretical studies based on the necking condition in tensile test, i.e., Considère's criterion [6]. Effects of yield strength [3] and work hardening of each layer were considered [7]. However, they are conditions only depend on stress state, so it is hard to consider (b) rolling conditions and combined effects.

The authors conducted non-steady-state finite element analyses on cold rolling of sandwich sheets, and reproduced periodical necking of the inner layer using uniform material properties over the length [8]. Effects of (a) material conditions were studied. It was confirmed that (1) larger difference in flow stresses and (2) lower work hardening of the hard layer, are major factors to cause periodical necking. In this study, effects of rolling conditions were investigated through FE analyses of some ideal single-pass rolling. Multi-pass cold rolling experiments of three type of sandwich sheets was conducted. Based on the FE and the experimental results, a plane-strain compression model was proposed. The predictions based on change in strain energies show good agreement with the experiment.

2. Effects of rolling conditions on periodical necking

2.1. Numerical method and conditions

Non-steady-state analyses were performed to reveal the effects of rolling conditions on the periodical necking, using a commercial finite element software ABAQUS Standard version 6.14. 2D plane-strain condition without lateral spreading was assumed. A three-layered clad sheet 0.6 mm in total thickness (0.2 mm in layer thickness) and 180 mm in length was considered. The sheet was divided into single mesh of 4-node square elements. The 3-layered structure was represented by giving different material properties to elements layer by layer. In other words, no relative sliding was allowed on the two interfaces between the layers. Both the inner and the outer layers were elastic-perfectly plastic bodies with Young's modulus of 200 GPa, Poisson's ratio of 0.3. Yield stress $Y_H = 1$ GPa, was prescribed to the inner layer, while yield stress $Y_S = 0.25$ GPa, was prescribed to the outer layers. No work hardening was assumed for both the inner and the outer layers.

One-pass rolling with reduction in thickness $r = 20\%$ was analyzed. The rolls of 130 mm in diameter D were assumed to be rigid. The friction coefficient between the rolls and the sheet μ was assumed to be 0.1. These were the standard conditions. Analyses were also conducted with independently varied (a)

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thickness reduction r = 10, 20, 30, 40% and (b) roll diameter D = 65, 130, 260, 520 mm.

2.2. Numerical results

Snapshots of longitudinal profiles of the hard layer (red) and the soft layers (blue) around the roll bite are shown in Figs. 1 and 2. The vertical dashed lines in the figures indicate the position of the minimum gap between the rolls. For quantitative discussion of periodical necking, degree α and wavelength λ are indicated in the figure. Degree of necking α is defined as follows [9],

$$\alpha = 1 - (t_{\min}/t_{\max}) \tag{1}$$

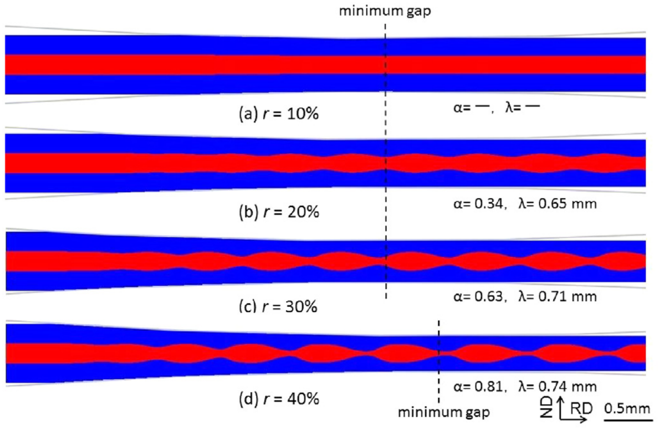

Fig. 1. Profile around the roll bite as a function of reduction in thickness r (D =130 mm).

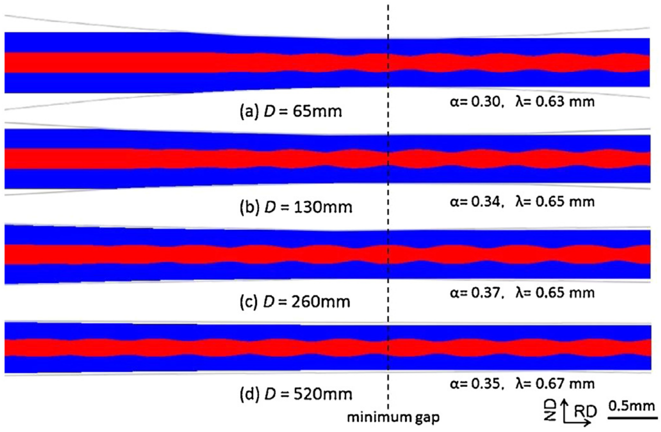

Fig. 2. Profile around the roll bite as a function of roll diameter D (r = 20%).

where $t_{\min}$ and $t_{\max}$ are the minimum and the maximum thickness of the inner layer after rolling. Wavelength λ of necking is defined as the average spacing between two adjacent necks.

Fig. 1 shows profiles as a function of reduction in thickness r. In case of small reduction (r = 10%), all the three layers deform uniformly and no neckings are observed (Fig. 1(a)). Under the standard conditions of r = 20% (Fig. 3(b)), periodical necking takes place. It is found that necks initiate after entering the roll bite and moves downstream with the sheet. Amplitude of necking increases gradually in the roll bite. In rolled sheets, degree α as well as wavelength λ increases with increasing reduction in thickness r. These effects of reduction qualitatively agree with experimental results in literature [9].

Fig. 2 shows profiles as a function of roll diameter D. Although the contact length clearly increases with roll diameter in the figure, degree α and wavelength λ do not much depend on roll diameter.

It is found that necking is well promoted with increasing reduction and is not sensitive to roll diameter, although necking of FE analyses is somehow exaggerated because of no work-hardening.

3. Evolution of necking in cold rolling experiments

Multi-pass cold rolling was conducted to reveal necking evolutions experimentally. Three types of clad sheets 30 mm in width and 100 mm in length were used. As tensile test of the layers were difficult because separation of layers from the bonded clad sheets introduce damage or strain, hardness test was conducted. Thickness and hardness of layers are listed in Table 1. Material 1 and 2 had a Fe-36%Ni layer sandwiched by copper layers. Material 1 was annealed to Material 2 so that Material 2 showed lower hardness. Material 3 had an austenitic stainless steel (type 304) layer sandwiched by Al–Mg alloy (A5052) layers. Total thickness of Materials 1 and 2 was 1.01 mm, while that of Material 3 was 0.50 mm. Thickness ratio of upper: center: lower layers of Material 1 and 2 was roughly 1:1:1, while that of Material 3 was 1:2:1. The clad sheets were cold-rolled on a rolling mill with lubricated rolls 70 mm in diameter at 3.30 m/s. Total reduction above 65% was applied by multi-pass operation.

Table 1
Thickness and hardness of layers in the three type of clad sheets used in cold-rolling experiments.

Material (thickness/mm)	Upper layer Center layer Lower layer	Layer thickness/mm	Vickers hardness, (HV)
Material 1 (1.009)	Copper	0.313	69
	Fe-36%Ni	0.353	220
	Copper	0.343	71
Material 2 (1.009)	Copper	0.303	69
	Fe-36%Ni	0.353	166
	Copper	0.353	70
Material 3 (0.498)	Al–Mg alloy A5052	0.131	105
	Stainless steel 304	0.241	363
	Al–Mg alloy A5052	0.126	106

Longitudinal sections of heavily rolled sheets are shown in Fig. 3. All the three clad sheets show periodical necking in center layer. Degree of necking α defined by Eq. (1) was measured on micrographs and shown in Fig. 4 as a function of total reduction. Degree α increases almost linearly with increasing reduction. Among the three clad sheets, necking of Material 3 is most pronounced, while that of Material 2 is least. Total reductions giving α = 0.2 are 57%, 65% and 52% for Material 1, 2 and 3, respectively. These reductions were estimated by interpolating experimental results shown in Fig. 4.

In order to investigate change in flow stress in cold rolling, Vickers hardness was measured around center of layers in several rolled sheets. Hardness changes against equivalent strain introduced by rolling ε are shown in Fig. 5. Equivalent strain was estimated by,

$$\varepsilon = -\frac{2}{\sqrt{3}}\ln\left(\frac{t_1}{t_0}\right) = -\frac{2}{\sqrt{3}}\ln(1-r) \tag{2}$$

where t_0 and t_1 are thicknesses of the layer before and after the rolling, respectively.

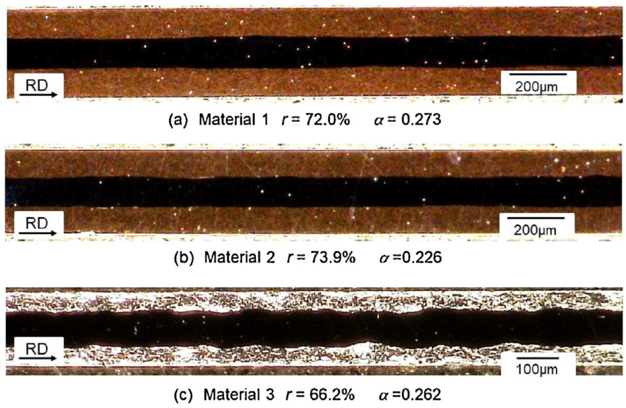

Fig. 3. Longitudinal section of heavily rolled sheets.

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