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Experimental and numerical modeling of flatness defects in strip cold rolling

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ABSTRACT

The manufacturing of sheets with high mechanical yield stress, low thickness and minimal flatness defects is a major challenge in the cold rolling of aluminum alloys or steels. Compressive residual stress may appear due to the manufacturing process and induce elastic wave buckling, leading to flatness defects. This study proposes an experimental setup to analyze the interaction between residual stress and buckling for wavy edge flatness defects. The residual stress is simulated by thermal stress. High-resolution full-field measurements are used to measure the wrinkling shape and thermal field. The influence of surface imperfections and global tension on the wrinkling characteristics is highlighted. Finite element tests are used for test validation.

1. Introduction

The manufacturing of sheets with high mechanical yield stress, low thickness and minimal flatness defects is a major challenge for the cold rolling of aluminum alloys or steels. Increased forces during the rolling induce higher deformation of the rolls and consequently a heterogeneous thickness reduction over the width of the strip. Then, compressive residual stress appears, and elastic wave buckling can be expected at the edges or the center of the strip (Fig. 1). It is thus important to understand the relationship between residual stress and wrinkling for better control of the strip flatness.

This problem has been investigated in the literature using mainly numerical or analytical approaches. Several simplified models are used to calculate the flatness defects in rolling. Some uncouple the buckling calculation from the calculation of the residual stress, assuming that the buckling does not affect the stress distribution in the bite. Fischer et al. (2000, 2003) and Rammerstorfer et al. (2001) use an analytical buckling calculation to characterize the buckling pattern at bifurcation. In Fischer et al. (2005), finite element calculations are used to study the post-buckling behavior of the strip up to full unloading. The deformed strip-plate after being cut off from the long strip and laid down on a rigid surface is also considered. Abdelkhalek et al. (2009) used the asymptotic numerical method to calculate the buckling and post-buckling of a laminated strip. Damil and Potier-Ferry (2010) compared a technique using slowly varying Fourier coefficients and the asymptotic Landau–Ginzburg approach to define simple macroscopic models describing the influence of local wrinkling on the membrane behavior. A few of these models couple the buckling calculation and the residual stress calculation (Counhaye, 2000; Abdelkhalek et al., 2011) using a simple macroscopic model (Roddeman et al., 1987) to account for buckling.

The authors did not find any experimental study to validate the models. An in-situ instrumentation of the rolling mill is not suitable for obtaining the residual stress distribution of the strip directly, easily and accurately, as it depends on several coupled aspects of physics (e.g., elastic–viscoplasticity, tribology, and thermic) (Hacquin et al., 1996; Montmitonnet, 2006; Nakhoul et al., 2014). Indeed, local residual stress distribution along the width (for one abscissa in the rolling direction) may be measured by tensiometer rolls, but the resolution of the sensors in the transverse y-direction is insufficient for a high-stress gradient region (Fig. 2).

Hence, this paper proposes a custom experimental setup to analyze the interaction between residual stress and buckling in the framework of rolling, focusing on manifested wavy edge flatness defects. “Manifested” means here that the flatness defects occur during the rolling process when the strip is subject to tension, in contrast to “latent” flatness defects that arise when the interstand tension is released.

Thermo-mechanical loading is applied to a strip to simulate the stress distribution during rolling. Global tension is applied to reproduce the interstand tension. Local thermal patches disturb

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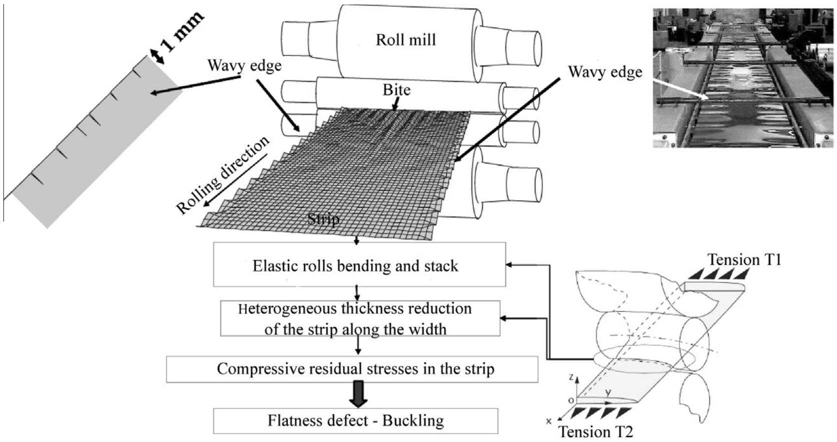

Fig. 1. Flatness defects in rolling (Abdelkhalek et al., 2011).

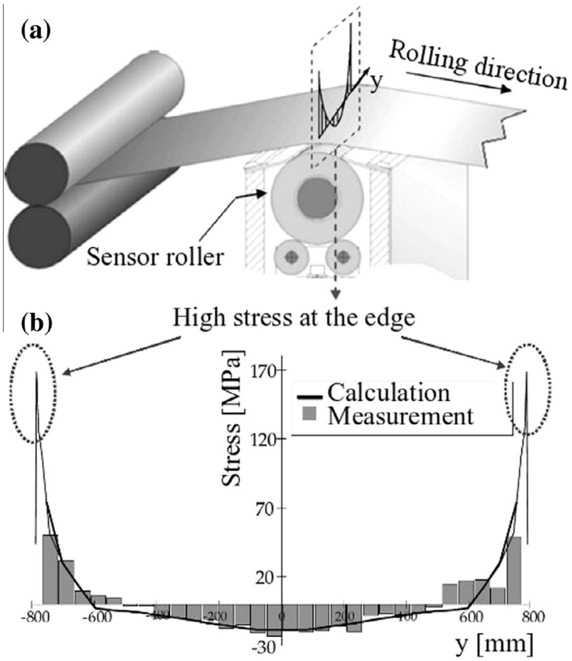

Fig. 2. Residual stress measurement by tensiometer rolls. (a) Tensiometer rolls (Abdelkhalek et al., 2011); (b) comparison of the measurement and calculation (Counhaye, 2000; Abdelkhalek et al., 2011).

the tensile stress state to simulate the self-equilibrating residual stress responsible for buckling. Thermal buckling has been well established since the late 1950s; see, for example, the review articles of Tauchert (1991) and Thornton (1993). As buckling is of concern, specific attention to the boundary conditions and the mid-surface imperfections is necessary to analyze the tests. These conditions are met in this study by the setup for full-field measurements.

Hence, this paper first aims to provide high-resolution results of thermo-mechanical buckling experiments applied to the framework of flatness defects during the cold rolling of thin sheets. Second, the results on the flattening role of the global tension, which was already investigated at the bifurcation and post-buckling levels by Rammerstorfer et al. (2001) and Fischer et al. (2005), are used to validate the setup.

The paper is organized as follows. The experimental and numerical methods are presented first. Second, the results of a representative test and its numerical simulation are described. Finally, the influence of the pre-tension load is emphasized.

2. Experimental setup

The raw material is a middle carbon steel manufactured by rolling. It is annealed and skin passed. The specimen (Fig. 3) is cut off from the strip by a shearing machine. The specimen is 800 mm long and 210 mm wide (Rolling direction – RD), and its thickness varies in the Y direction between 0.326 mm at the edges and 0.336 mm at the center. Its behavior is characterized by uniaxial tensile tests conducted at room temperature. The elastic properties are as follows: Young's modulus $E = 205.7$ GPa, Poisson's ratio $\nu = 0.28$, yield stress $\sigma_{0.2} = 420.8$ MPa.

During cold rolling, the stress state of the sheet between two rolling stands is considered as stationary in the rolling direction. It is the combination of a global tension (interstand tension) and a residual membrane stress that is self-equilibrated in the transverse direction (Rammerstorfer et al., 2001).

Fig. 4 shows the experimental setup. The specimen is clamped to a frame by ball-jointed grips. The inter-grips length is 731 mm long. The interstand tension is simulated by a global force applied by a lever system.

In addition to the global tension, the self-equilibrating residual membrane stress distribution is simulated by thermal stress. Local heating is applied at the edges by quartz infrared emitters (HERAEUS, heated length 400 mm, width 23 mm, and nominal power 2480 W). The distance between the lamps and the surface of the plate is approximately 4 cm. The two heated surfaces (width $B0 = 25$ mm, length $L0 = 400$ mm, red in Fig. 3) are painted matte black to maximize the absorption of the radiation, whereas the cold part of the heated side is polished to minimize it.

The temperature is locally measured by type K thermocouples (wire diameter 0.3 mm). The thermocouples, TCi in Fig. 3, are spot-welded on the surface. The thermal full-field is measured by a MICROEPSILON thermoIMAGER TIM 400 infrared camera (resolution 382 × 288 pixels). The temperature is averaged over 1–1.5 mm^2. The infrared camera accuracy is ±2 °C. Thermocouples are used to set its emissivity parameter.

In addition to the thermal measurement, a full-field measurement of the out-of-plane coordinate is performed by three-dimensional digital image correlation (3D-DIC) (Chu et al., 1985; Luo et al., 1993) using the VIC 3D commercial software (Vic-3D, 2010). Two Pike F-1100B cameras are combined with Xenon-Emerald 50/2.2-F-S lenses. The resolution of the cameras is 4008 × 2672 pixels. A random gray level pattern is achieved by