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Theoretical analysis of minimum metal foil thickness achievable by asymmetric rolling with fixed identical roll diameters

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Abstract: A novel approach is proposed for computing the minimum thickness of a metal foil that can be achieved by asymmetric rolling using rolls with identical diameter. This approach is based on simultaneously solving Tselikov equation for the rolling pressure and the modified Hitchcock equation for the roller flattening. To minimize the effect of the elastic deformation on the equal flow per second during the ultrathin foil rolling process, the law of conservation of mass was employed to compute the proportions of the forward slip, backward slip, and the cross shear zones in the contact arc, and then a formula was derived for computing the minimum thickness for asymmetric rolling. Experiment was conducted to find the foil minimum thickness for 304 steel by asymmetric rolling under the asymmetry ratios of 1.05, 1.15 and 1.30. The experimental results are in good agreement with the calculated ones. It was validated that the proposed formula can be used to calculate the foil minimum thickness under the asymmetric rolling condition.

Key words: minimum thickness; metal foil; law of mass conservation; asymmetric rolling

1 Introduction

In recent years, the demand for micro-electromechanical systems (MEMS) products has been increasing. The development of novel micro-manufacturing technologies is receiving much attention [1,2]. The application of these new manufacturing technologies also extends to ultrathin foils [3]. With the development of the micro-forming technology [4−6], it is necessary to make the foils to be thinner and thinner, at the same time to maintain their excellent mechanical properties [7] and physical properties [8].

Asymmetric rolling offers the advantage of a reduced roll force and allows to improve the mechanical properties of products. For instance, ZUO et al [9] utilized this rolling technique and acquired a pure aluminum sheet with a grain size of 500 nm. WRONSKI et al [10,11] studied the grain refinement in 6061 aluminum alloys under asymmetric rolling conditions. LIU and KAWALLA [12] found that asymmetric rolling yields a greater recrystallization volume fraction and a smaller average grain size in the central layer of austenitic steel than symmetric rolling.

In traditional rolling processes, the thickness of a foil cannot be reduced below the theoretical minimum rolling thickness [13,14], not even at the expense of a greater roll force or additional rolling passes. But asymmetric rolling allows to break the limit of the traditionally achievable minimum thickness, thus making it possible to produce thinner rolled foils.

However, the theoretical determination of the possible minimum rolling thickness (PMRT) achievable by asymmetric rolling is still an unsolved problem. Compared to symmetric rolling, several experiments have demonstrated that a thinner metal foil can be achieved by asymmetric rolling [13]. YU et al [14] produced a copper foil with a thickness of only 0.005 mm by asymmetric rolling, which is considerably lower than the PMRT limit for symmetric rolling. TANG et al [13,15] later proposed an implicit form of a PMRT equation for asymmetric rolling based on the Stone formula (i.e., the rolling process was treated as a plane upsetting process). However, this formula was derived

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on the premise that the length of the forward slip zone is equal to that of the backward slip zone, which is not the case during the real rolling process because the stress distribution in the contact arc is much more complicated when considering the cross shear zone. In general, so far, there are very few studies on the PMRT achievable by asymmetric rolling.

Studies on the neutral angle and the forward/backward slip during the rolling process are mainly based on the law of equal volume flow per second in traditional rolling theory [16]. However, under PMRT conditions, only elastic deformation occurs in the deformed zone between the roll and the foil. Therefore, in this case, the law of equal volume flow per second is not applicable due to the elastic change in volume.

This study aimed at establishing a new PMRT equation which is more suitable to describe the characteristics of asymmetric rolling. This novel equation for calculating the minimum asymmetric rolling thickness (MART equation) was deduced from the static equilibrium equation and the law of conservation of mass.

2 Theoretical considerations

2.1 Derivation of PMRT for asymmetric rolling

The stress state of the deformation region is different when comparing the asymmetric and the symmetric rolling process. A cross shear zone occurs in the rolling area during the asymmetric rolling process, and the shear stress in this zone leads to a significant reduction of the hydrostatic pressure, which is the key factor that allows to break the PMRT limit of the symmetric rolling process. In order to better understand the differences between these two rolling processes, the contact deformation region is divided into several parts: for the symmetric rolling process, the division is shown in Fig. 1(a), and for the asymmetric rolling process, the division is shown in Fig. 1(b).

In Fig. 1(a), v is the linear velocity of the rolls in the case of symmetric rolling. The contact region is divided

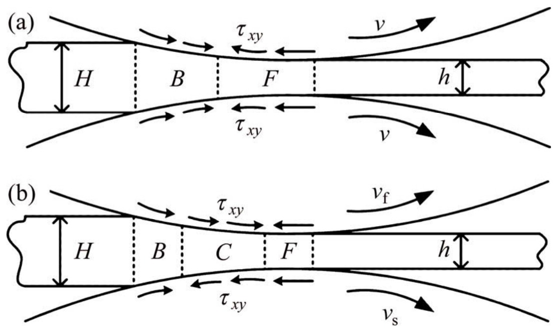

Fig. 1 Comparison of contact deformation regions for symmetric and asymmetric rolling: (a) Symmetric rolling; (b) Asymmetric rolling

into the forward slip zone (i.e., F) and the backward slip zone (i.e., B). The friction on the upper and the lower surfaces is considered to be equivalent. In the symmetric rolling process, the vertical compressive stress is the highest around the neutral point, and the peak value of the contact pressure appears here, which is not conducive to further foil thinning.

For asymmetric rolling, since the velocities of the upper and the lower rolls are different, the contact region must be divided into three parts: the forward slip zone, the cross shear zone (i.e., C) and the backward slip zone, as shown in Fig. 1(b). In the cross shear zone, the friction vectors for the upper and the lower surfaces are pointing in the opposite direction, resulting in a state of strong shear stress in the foil, which allows the stress to reach the yield point. When comparing asymmetric and symmetric rolling, the forward slip zone and the backward slip zone are similar. The pressure distributions for both the forward slip zone and the backward slip zone are derived from Tselikov formula. If the tension is ignored, the formulae can be expressed as follows:

$$p_\mathrm{f}=\frac{K}{\delta}\left[(\delta+1)\left(\frac{h_x}{h}\right)^{\delta}-1\right]\text{(Forward slip zone)} \quad (1)$$

$$p_\mathrm{b}=\frac{K}{\delta}\left[(\delta-1)\left(\frac{H}{h_x}\right)^{\delta}+1\right]\text{(Backward slip zone)} \quad (2)$$

with

$$\delta=\frac{2\mu l}{\Delta h_\mathrm{p}}$$

where p_b and p_f refer to the rolling pressures in the backward slip and the forward slip zones, respectively; K is the plane deformation resistance; h_x is the foil thickness at any location of the contact arc; H is the foil thickness at the entrance; h is the foil thickness at the exit; l is the length of the contact arc; μ is the friction coefficient; and Δh_p is the difference in thickness, i.e., $\Delta h_\mathrm{p}=H-h$. Under PMRT conditions, the elastic deformation of the rolls and the metal foil can no longer be ignored. The pressure distribution along the contact arc in the cross shear zone can be approximated as a straight line, and the following equation can be deduced from Fig. 2:

$$\begin{cases} p_\mathrm{b}(a)=p_\mathrm{c}(a) \\ p_\mathrm{f}(b)=p_\mathrm{c}(b) \end{cases} \quad (3)$$

Figure 2 shows the distribution of the rolling pressure along the contact arc for asymmetric rolling. The lengths of the contact region, the backward slip zone, the cross shear zone and the forward slip zone are denoted as l, $\lambda_\mathrm{B}l$, $\zeta\, l$ and $\lambda_\mathrm{F}l$, respectively.