Investigation of Slip Occurrence in the Ring Rolling Process

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Abstract. Ring rolling is a hot forming process for producing rings that have large diameters when compared to their cross sections. This process is very dynamic and involves considerable variations in ring shape and size. One of the failure modes in ring rolling processes is slip that occurs when a thickness reduction, exceeds the limit value. The thickness reduction depends on the tool speed and dimensions as well as ring size, and varies over time. This paper reports results of a study investigating the thickness reduction with respect to slip occurrence. In terms of wall thickness reduction, the process can be divided into three distinct stages (excluding the sizing stage): (i) initial stage corresponding to the first revolution of the roll, (ii) main stage, when the proper ring rolling takes place, (iii) final stage, when the main roll does not move in an axial direction but the ring is being formed during one revolution of the tool. It has been found that the most slip-prone moment is the end of the second and the beginning of the third stage of the ring rolling process, when the wall thickness reduction is the highest. Based on a comparison of the calculated thickness reduction and its limit values, it could be predicted whether slip would occur, and if so – in what stage of the rolling process. Numerical results and experimental findings are in good agreement.

1. Introduction

Products obtained by ring rolling are widely used by different industrial branches in the production of parts in which the ring diameter is considerably bigger than its cross section. A significant advantage of the ring rolling process is its high productivity [1, 2]. This high productivity, however, depends on tool speed parameters, therefore attempts are made to make these speeds the highest possible. Nevertheless, the ring rolling process is not free from failure modes such as product defects or the occurrence of undesired phenomena such as slip. The importance of problems related to tool speed parameters in ring rolling processes has been stressed in numerous studies. Yan et al. [3] determined the relationship between the feed rate and the ring outer diameter growth rate in cold ring rolling. Allegri et al. [4] used FEM simulations to investigate the effect of the rotational speed of the main roll on the product geometry as well as force and energy parameters in hot ring rolling. Sun et al. [5] determined the effect of the main roll rotational speed and feed rate on temperature and strain non-uniformity in hot ring rolling. The problem of the effect of tool speed on the workpiece temperature was also investigated in works [6, 7]. Hua et al. [8] studied, among others, effects of parameters in radial-axial ring rolling. Studies investigating the effect of tool speed on the rolling process often omit such fundamental failure mode as slip. There are relatively few studies devoted to this problem. Lin and Zhi [9] and Qian et al. [10] established, among

others, the formulas for calculating the maximum possible thickness reduction which cannot be exceeded if slip is to be avoided. The authors of the above studies draw attention to the fact, that a too high thickness reduction which depends on, among others, tool speed parameters leads to slip occurrence. The proposed formulas for calculating thickness reduction in rolling are hard to apply in practice due to the fact that they use momentary values of ring radius which undergoes variations during the rolling process. In a likewise manner, it is difficult to determine thickness reduction during the rolling process.

A survey of the specialist literature demonstrates that despite a number of works investigating the ring rolling process with respect to slip occurrence, this problem has not been thoroughly examined. It has therefore been considered justified to undertake a study investigating effects of tool speed and dimension-related parameters on the occurrence of slip in the ring rolling process.

2. Thickness reduction analysis

In this study, a radial ring rolling process wherein only the main roll performs both rotational and feed motion (Fig. 1) is analysed. On a mandrel 2 is mounted a billet 3 in the form of a pre-formed ring. The ring is deformed by the action of a main roll 1. The roll moves radially with a constant velocity V_l towards the mandrel causing reduction of the billet cross-section, and it also rotates with a constant speed n_l causing the ring 3 to rotate and thus leading to a resultant revolution of the mandrel 2.

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Temporary thickness reduction is described with the following relationship:

$$\Delta h = H - h \quad (1)$$

where: H – ring thickness prior to entering the deformation zone, h – ring thickness after leaving the deformation zone.

Figure 1. Schematic design of the radial ring rolling process: a) start of Stage I, b) start of Stage II, c) start of Stage III, d) end of Stage III; 1 – main roll, 2 – mandrel, 3 – billet.

To prevent slip, the temporary thickness reduction described with Equation (1) cannot exceed the limit value Δh_{limit} expressed with a formula developed by Lin and Zhi [9]:

$$\Delta h \leq \Delta h_{limit} = \frac{2\beta^2 R_1}{(1+R_1/R_2)^2} \left(1 + \frac{R_1}{R_2} + \frac{R_1}{R} - \frac{R_1}{r} \right) \quad (2)$$

where: R_1 – radius of the main roll, R_2 – radius of the mandrel, R – current outer radius of the ring, r – current inner radius of the ring, $\beta = \tan^{-1} \mu$, where μ – friction coefficient.

Here one must calculate the value of Δh for every moment of the rolling process, as this will enable to determine the maximum thickness reduction Δh_{max} . By comparing Δh_{max} and Δh_{limit} one can estimate if slip will occur during the rolling process.

Based on obtained results, it was assumed that depending on the thickness reduction Δh , this process could be divided into three stages.

Stage I of the rolling process corresponds to the first revolution of the ring (Figs. 1a, b). In this stage, the ring thickness prior to entering the deformation zone is equal to the initial ring thickness:

$$H = H_0 = R_0 - r_0 \quad (3)$$

where: R_0 – initial outer radius of the ring, r_0 – initial inner radius of the ring, H_0 – initial radial thickness of the ring.

The thickness reduction is therefore equal to the radial displacement of the main roll:

$$\Delta h_I = V_I \cdot \Delta t \quad (4)$$

where: V_I – feed rate of the main roll, Δt – unit time interval.

In Stage II, the ring thickness H prior to entering the deformation zone is not constant any longer – its value decreases with revolution of the ring (Figs. 1b, c). The thickness reduction Δh_{II} results from the main roll's radial motion and the decreasing ring thickness:

$$\Delta h_{II} = V_I \cdot \Delta t - \Delta H \quad (5)$$

where ΔH is thickness reduction prior to entering the deformation zone over a time Δt .

Stage II of the rolling process lasts until the main roll has been stopped ($V_I = 0$), i.e., it ends when the distance between the main roll surface and the mandrel is equal to the final thickness of the ring.

In Stage III (Figs. 1c, d), when the main roll is only rotated, the ring thickness after the exit from the deformation zone is constant and equal to H_k . The ring thickness prior to entering the deformation zone is variable (decreases with rotation), and the thickness reduction is equal to:

$$\Delta h_{III} = H - H_k, \quad (6)$$

where H – ring thickness prior to entering the deformation zone, H_k – the final ring thickness.

This stage ends when the ring has completed a full revolution and its thickness H_k is constant over the entire circumference. In this stage, Δh_{III} decreases to zero.

Thickness reduction in individual stages of the rolling process can be calculated numerically. Fig. 2 schematically plots thickness reduction versus time for the entire rolling process. It can be observed that in Stage I Δh_I increases linearly with time, this increase being dependent on the main roll feed rate V_I . In Stage II, Δh_{II} continues to increase, even though the growth rate is lower than in Stage I, and its dependence on time is no longer linear. The thickness reduction depends on the main roll feed rate and the thickness reduction prior to entering the deformation zone, H , which depends on, among others, the circumferential velocity of the main roll ($V_0 = n_1 \cdot R_1$). At the end of Stage II, the thickness reduction is the highest. Slip does not occur provided that the maximum value of Δh_{max} does not exceed the limit value Δh_{limit} , i.e., Equation (2) is satisfied. In Stage III of the rolling process, the thickness reduction decreases to zero. The plot also shows three different lines denoting the limit values of thickness reduction Δh_{limit} . If the thickness reduction Δh does not exceed the limit line at any moment of the rolling process, as is the case with limit line 1, slip will not take place. If Δh exceeds the limit value at any moment of the rolling process, slip will occur. This can occur either in Stage II (limit line 2) or Stage I (limit line 3). Slip should not occur in Stage III of the rolling process.

Figure 2. Plot illustrating thickness reduction during the rolling process.

3. Experimental methods

Experimental tests were performed on a rolling mill D51Y-160E. The main roll has an outside diameter of 380 mm, while the mandrel is 36 mm in diameter. Rolling tests were performed on a ring-shaped billet with the dimensions $\varnothing 110 \times \varnothing 50 \times 15$ mm and made of C45 steel (1.0503). The billet was preheated to 1100 °C, mounted on the mandrel and deformed until it reached the final thickness of 14 mm. The objective of this part of the

study was experimental verification of the slip prediction concept described in Section 2 of the present paper. To this end, three rolling tests were performed in compliance with the parameters listed in Tab. 1.

Table 1. Parameters used in investigation of slip occurrence.

No. of test	V_L , mm/s	n_L , rev/miv	V_0 , mm/s	Slip phenomenon
1	5	54	1073.9	No
2	17	54	1073.9	Yes
3	40	54	1073.9	Yes

4. Results and discussion

Results of the rolling tests performed according to the parameters listed in Tab. 1 significantly differ. The ring obtained in Test 1 is correct (Fig. 3a), while products obtained in Tests 2 and 3 have defects due to the occurrence of slip. In Test 2, the slip occurred in Stage II of the rolling process (Fig. 3b), whereas in Test 3 it occurred in Stage I (Fig. 3c).

Figure 3. Rings obtained from rolling tests performed in accordance with parameters in Tab. 1: a) Test 1 – correctly shaped ring, b) Test 2 – slip in Stage II, c) Test 3 – slip in Stage I.

Fig. 4 shows thickness reduction versus time and limit lines calculated based on Equation (2) for every tested rolling case. The Coulomb friction coefficient was set equal to $\mu=0.5$. As regards Test 1 (Fig. 4a), the thickness reduction Δh during the entire rolling cycle is below the limit line. This means that the condition in Eq. (2) is

satisfied, and hence slip should not occur. This is confirmed by experimental results, as the obtained product is defect-free (Fig. 3a). In the two other rolling cases, the thickness reduction exceeds the limit value, which should cause slip (Figs. 4b, c).

Figure 4. Thickness reduction during rolling: a) Test 1, b) Test 2, c) Test 3.

Experimental results of Test 2 demonstrate that slip occurred in Stage II. However, according to the calculations, it should have occurred in Stage I (Fig. 4b).

In this case, the numerical results and experimental findings do not agree with respect to slip occurrence moment prediction.

It is worth mentioning that in Test 3, the feed rate of the main roll is so high that its feed motion in the final position ($V_f=0$) is stopped before the ring has completed a full revolution. In this case (Fig. 4c), Stage II does not take place at all; Stage I is followed immediately by Stage III, wherein the main roll only performs rotational motion. The thickness reduction Δh is so high that it exceeds the limit value in Stage I, which should cause slip. Experimental results confirm this prediction. Slip indeed occurs in Stage I of the rolling process, and hence the product is defective (Fig. 3c).

5. Conclusions

Obtained results lead to the following conclusions:

1. Thickness reduction during the rolling process is significant in terms of slip occurrence. Three stages of thickness reduction can be distinguished in the rolling process. The highest thickness reduction occurs at the end of Stage II, i.e., when the main roll is stopped. The rolling process proceeds correctly provided that this parameter does not exceed the limit value.

2. The employed research methods enable to determine whether slip will occur. The only constraint of this methodology is the necessity of using numerical methods to calculate the thickness reduction Δh . It is therefore advisable to develop a mathematical formula for calculating this parameter. This would enable to predict slip occurrence already at the stage of process design.

3. The ratio between the circumferential velocity and the feed rate of the main roll is of vital importance in terms of slip occurrence. The higher the feed rate relative to circumferential speed of main roll, the higher the thickness reduction Δh and the greater the risk of slipping.

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