International Journal of Mechanical Sciences 123 (2017) 311–323

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Temperature estimation and slip-line force analytical models for the estimation of the radial forming force in the RARR process of flat rings

Luca Quagliato[*], Guido A. Berti

Department of Management and Engineering, University of Padua, Stradella San Nicola 3, 36100 Vicenza, Italy

ARTICLE INFO

Keywords:
Ring rolling
Temperature estimation
Slip-line
Force prediction
FE analysis

ABSTRACT

In this study, a mathematical model for the prediction of the temperature evolution in the ring during the radial-axial ring rolling process is developed and used, together with the authors' previous results, to determine analytically the flow stress of the material during process. These results, combined with Hill's slip-line field solution adapted to the RARR process, allow a fast and reasonably precise calculation of the radial forming force, a key parameter at the preliminary stage of the process design. The approach is validated by applying the proposed model to a case available in the literature and comparing the analytical results with those of the laboratory experiment and FEM simulation. Following the successful comparison, the models were applied to a large variety of flat rings, comparing analytical predictions with the results of FEM simulations. The accuracy of the analytical calculation and the reliability of the proposed models, for different ring configuration and process parameters, are presented and discussed.

1. Introduction

Radial-axial ring rolling (RARR) is a multi-stage manufacturing technique that allows the production of seamless and near-net-shape forgings made from various materials and with various shapes [1]. The ring rolling technique has evolved over 150 years with significant research work over the last 40 years [2]. In recent years, the introduction of FEM simulation has radically widen the possibilities of investigation and improvement in the RARR process. However, the development of algorithms capable of reducing the number of FEM simulations required to obtain the best configuration of set-up parameters would still be very helpful. This is particularly requested in the industrial applications in order to reduce the time required for the design of the process. The design phase of many manufacturing processes, including the RARR process, must take into account technological constraints, such as the maximum forming force of the available machines. For this reason, an algorithm capable of quickly calculating the process forces, and hence allowing the process planner to explore many different combinations of process parameters, would be very useful in both industrial and research environments.

In the last 70 years, much effort has been spent in the development of different techniques for calculating the forces in the RARR process. These include the FE methodology by Zhou et al. [1] and by Guo et al. [3]; the SLAB method by Parvizi et al. [4]; the upper bound analysis by Parvizi et al. [5]; and the slip-line method by Hawkyard et al. [6] and by Mamalis et al. [7]. If properly set-up, the FE methodology can give a precise estimation of the process forces but it is a very time-consuming technique, especially if many different combinations of process parameters have to be explored. The upper-bound method can overestimate the force prediction since only the velocity field is taken into account. On the other hand, if the velocity field is neglected and only the stress field is considered, the calculation results in an underestimation of the process forces.

In this context, the aims of the present research work are twofold. The first is the development of an algorithm capable of predicting the average temperature evolution resulting from the combination of conductive, convective and radiant heat exchange in the ring during the process. This area has not yet been fully explored in the literature. The second aim is to use the resultant temperature prediction, together with the authors' previous results related to geometry, strain and strain rate estimation [8,9] to calculate the flow stress of the material at each round of the process. This allows the calculation of the radial forming force by adapting the Hill's slip-line solution developed for flat indenters to the RARR process [10].

The analysis performed by Hawkyard et al. [6], based on the Hill's slip-line solution for the indentation of a slab by opposite flat indenters [10], is extended here to the hot ring rolling process for a range of rings having final diameters from 650 mm to 2400 mm. In order to understand the influence of the ring section geometry on the quality of the force prediction, three cases with different ratios between final height and final thickness of the ring have been analyzed for each tested ring diameter.

---

[*] Corresponding author.

http://dx.doi.org/10.1016/j.ijmecsci.2017.02.008
Received 5 October 2016; Received in revised form 12 January 2017; Accepted 8 February 2017

The results of the temperature estimation show good agreement with the output of the FEM simulation, proving the reliability of the assumptions formulated for the description of the contact between the ring and the tools. Moreover, the calculation of the radial forming force will show how the slip-line solution reasonably approximates the FEM simulation for a wide range of rings and ring sections, but loses accuracy if the final diameter of the ring is sufficiently small, due to the difference of the contact zone with respect to the flat indenter condition. Since the average mandrel feeding speed has also shown to influence the forming force, as also anticipated by Ryoo et al. [11], the correlation between force estimation and average mandrel feeding speed is explored allowing a better interpretation of the results of the proposed approaches for the calculation of the radial forming force.

2. Analytical model for the estimation of the temperature evolution in the ring

In order to calculate the process forces in the mandrel-main roll deformation gap, the geometry of the ring section undergoing the deformation, its effective plastic strain, effective strain rate and temperature are required. Most of these data can be calculated from the initial and final shape of the ring and from the motion laws applied to the main-roll, the mandrel and the axial rolls, as detailed in [8,9]. As concerns the estimation of the temperature of the ring during the process, a laborious and complicated model, as suggested but not verified in [12], is out of the scope of this paper. For this reason, in this research work, the plastic deformation heat and the friction-caused heat are neglected. The simplified analytical model proposed in this paper takes in account conductive, convective and radiant heat exchange among the ring, the tooling system and the environment and allows estimating the temperature evolution in the ring during the process, with a limited error. Moreover, the proposed algorithm can be implemented easily in various software packages or calculation worksheets, making it possible to include it inside already existing codes and programs.

The purpose of this section is to define three different lumped heat exchange models: a conductive one for the mandrel-main roll deformation gap, a conductive one for the axial rolls deformation gap and a mixed convective-radiant heat exchange model applied to the whole ring (Fig. 1). These models will be applied following this order, assuming that: the conductive heat exchange between ring and mandrel/main roll acts only during the deformation in this gap; the conductive heat exchange between ring and axial rolls acts only during the deformation in this gap; and that the heat exchange between the ring and the environment acts only when the ring rotates between these two deformation gaps. The results of the calculation will be compared with the results of FE simulations, demonstrating the reliability of the proposed approach.

2.1. Conductive heat exchange model for the mandrel-main roll deformation gap

In this section, as first, some consideration about the contact geometry between ring and tools will be derived and later utilized as input parameters for the temperature model, where the contact area plays an important role in the prediction of the temperature. Considering that both mandrel and main-roll radii are normally greater than the projection of the contact arc between tools and ring, authors have chosen to assume a common projection for the contact arc on the x-axis, in terms of L_C, calculated utilizing Eq. (1) [13], as shown in Fig. 2. Each ring section enters the deformation gap with a specific initial thickness s_0 and exits it with a final one s_1. The size of the section is determined by its position in the ring and on the motion laws of the tools of the ring rolling mill.

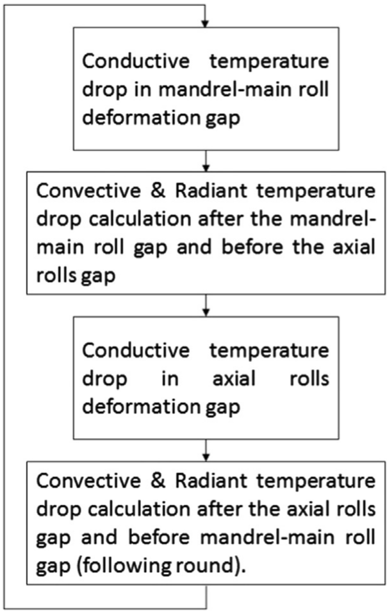

Fig. 1. Heat exchange models flow chart.

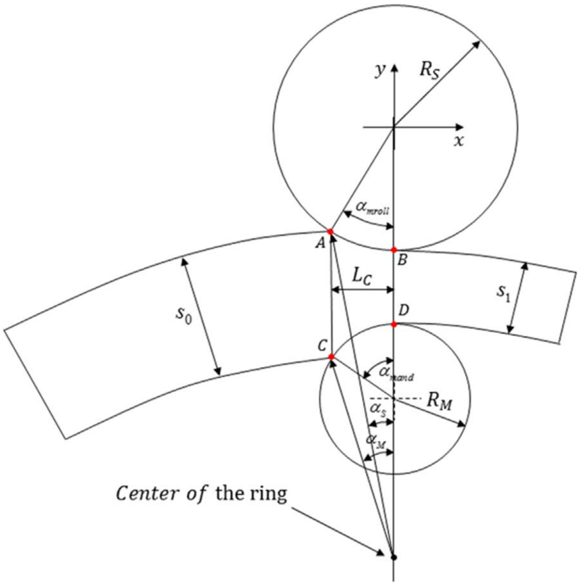

Fig. 2. Mandrel-main roll deformation gap.

$$L_C = \sqrt{\frac{2\Delta h}{\left(\frac{1}{R_S}\right) + \left(\frac{1}{R_M}\right) + \left(\frac{1}{R}\right) - \left(\frac{1}{r}\right)}} \tag{1}$$

R_S and R_M are the radii of main-roll and mandrel respectively, whereas r and R are the average inner and outer radius of the ring section undergoing the deformation, respectively.

Based on the values of L_C and r, or R, the contact angle α_M on the mandrel side, or α_S on the main-roll side, referred to the center of inner, or outer, radius of the ring, Fig. 2, can be calculated as in Eq. (2). Being the algorithm applicable to both contact zones, the following procedure will be derived considering the mandrel-inner ring radius contact zone, since it can easily be extended to the main roll-outer ring radius zone by substituting the relevant parameters.

$$\alpha_M = \arcsin\left(\frac{L_c}{r}\right) \tag{2}$$