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Slip line model for forces estimation in the radial-axial ring rolling process

Luca Quagliato [a,b,*], Guido A. Berti [a], Dongwook Kim [b], Naksoo Kim [b]

[a] University of Padua, Department of Management and Engineering, Stradella San Nicola 3, Vicenza 36100, Italy
[b] Sogang University, Department of Mechanical Engineering, 35 Baekbeom-ro, Mapo-Gu, Seoul 04107, Republic of Korea

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ABSTRACT

In the research presented in this paper, a slip line-based model is proposed for the estimation of both radial and axial force in the radial-axial ring rolling (RARR) process. Based on the shape of the contact arcs between ring and tools in the two deformation gaps present in the ring rolling process, a recursive algorithm for the calculation of the two slip line fields starting from the two pairs of opposite tools is derived and implemented in a commercial spreadsheet software (MS Excel). By considering the stress boundary conditions applied to the portion of material undergoing the deformation, both for the radial and axial deformation gaps, the pressure factors those make the two slip line fields starting from the two opposite tools to intersect are calculated and utilized for the estimation of radial and axial forces, for each round of the process. The developed model has been validated by cross-comparing its results with those of laboratory experiment and numerical simulation. For the validation study case, the average deviations, in comparison to the experimental results, are calculated in 1.86% and 4.55% for the slip line force model whereas in 6.86% and 0.88% for the numerical simulation, for the radial and axial forces respectively. The proposed slip line model has been also utilized for the estimation of radial and axial forming forces of nine different study cases of flat rings having the outer diameter ranging from 800 mm to 2000 mm, observing a maximum deviation, in comparison to the relevant FEM simulation, of 4.92% (radial force) and 5.88% (axial force). The developed slip line force model allows estimating almost in real time and with a reasonable accuracy the process forces and, for this reason, it may be of interest for both industrial and academic researchers dealing with the set-up and control of the radial-axial ring rolling process.

1. Introduction

Radial-axial ring rolling (RARR) is a wide-spread forging process that allows manufacturing seamless rings and is utilized for the manufacturing of components for many different industrial sectors, among them machinery, metallurgy, aerospace and automotive [1]. In the last sixty years, several authors focused their attention on the development of both analytical and numerical models for the analysis of both the kinematics and the dynamics of the ring rolling process, aiming to develop algorithms and procedures for a quick and precise estimation of the process forces during the process.

One of the first contributions concerning the development of an analytical force model for the ring rolling process is due to Hawkyard et al. [2]. In their contribution, based on the Hill's slip line flat indenter theory [3], a model for the estimation of both load and torque is developed and validated by comparing the results with those of ring rolling laboratory experiments, carried out at cold process conditions. One of the main limitations of the Hill's solution (flat indenters) [3] is the assumption of a straight contact line between tool and workpiece. As demonstrated in Quagliato and Berti [4], the fulfillment of this assumption is related to specific interactions between ring and tools diameters and fails to comply if the curvature of ring and tool, namely mandrel-main roll, become too similar. In this case, if the Hill's slip line solution for flat indenters is utilized, it results in an underestimation of the radial forming force up to almost 30%.

In a more recent work, Parvizi et al. [5] proposed a SLAB analysis for the determination of both load and torque in the ring rolling process but, based on the results presented in the paper, the model tends to underestimate both of them in case the mean radius of the ring is greater than 160 mm or in case of thickness reduction smaller than 40%. However, the thickness reduction and, especially, the ring diameter are normally not under the direct control of the process engineer and a variation of accuracy on their basis might be problematic

In fact, being the ring rolling an incremental forming process, the thickness reduction is not independent of the other process parameters and especially it is linked to the geometry of both ring and ring rolling mill, as initially suggested in the work of Lin and Zhi [6]. In addition to that, as proved in Berti et al. [7], the choice of the feasible ranges

* Corresponding author at: University of Padua, Department of Management and Engineering, Stradella San Nicola 3, Vicenza 36100, Italy.
E-mail address: quagliato@gest.unipd.it (L. Quagliato).

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for both mandrel and upper axial roll feeding speeds should be oriented toward the stability of the process hence to thickness reduction between 10% and 20%, in order to reduce the spreading effect in the vertical direction of the ring.

Again concerning the development of analytical models for the force estimation in the RARR process, Parvizi and Abrinia [8] developed a two-dimensional upper bound method for the estimation of the radial forming force and compared the results with both previous upper bound literature models and literature experiments, namely the works of Ryoo and Yang [9] and Yang and Ryoo [10]. The results shown that, for most of the explored range of mean ring radii, a higher accuracy in comparison to previous literature upper bound models [9,10] is achieved but the comparison is carried out only at the first round of the rotation, which is normally not the round where the maximum force arises.

Concerning analytical models for the estimation of the axial forming force, only two recent contributions seem to be available. Wang and Wang [11] established a SLAB-based analytical model for the estimation of the forming force in the axial rolls deformation gap, presenting the results of its application on different study cases, where both inner and outer diameters of the rings have been varied. However, since no comparison with neither numerical nor experimental results is presented, the accuracy of the model is unknown. Same concerning the analytical estimation of the axial forming force, Kalyani et al. [12] presented a force equilibrium-based model for the estimation of both radial and axial forming force and compared the results with those of laboratory experiments. However, the comparison is carried out only at 60 s and 180 s and not for the whole rolling time, making it complicated to understand whether the maximum value of the axial forming force is well predicted or not. In addition to that, the maximum error in the estimation of the axial forming force, in comparison to the relevant experiment, is estimated in 16.9%, a deviation that may be considered too high for certain industrial or research applications.

In relation to the estimation of the forming force in the radial-axial ring rolling (RARR) process by means of numerical simulation, several authors developed different approaches and techniques to reduce the computational time while preserving or increasing the accuracy of the calculation. Yea et al. [13] developed a finite element code, namely SHAPE-RR^{TM}, specially designed for the ring rolling process, and utilized it for the calculation of spread, pressure distribution and roll force. The results have been compared with previous experimental works, proving the reliability of the developed software. In a subsequent work, Kim et al. [14] utilized the same SHAPE-RR^{TM} code for the computation of the optimal mandrel and upper axial roll feeding speeds in order to minimize the load in the ring rolling process, validating the relevant results with industrial study-case experiments.

Concerning different integration approaches, Davey and Ward [15] developed an arbitrary Lagrangian–Eulerian strategy for the reduction of the computation time, in comparison to conventional Lagrangian approaches. The application of the proposed method allows reducing the nodes of the mesh to a range between 17.5% and 25% in comparison to the original full Lagrangian approach mesh system while granting a good agreement with experimental results. Lim et al. [16], by utilizing an implicit finite-strain updated-Lagrangian approach, developed a material mesh-computational hybrid numerical model for the reduction of the computational-time. The results showed a considerable computational-time reduction, estimated in 70%, in comparison to standard finite element technique but, although the considerable reduction, the computational time was still relatively high. In addition to that, in a recent work of Kim et al. [17], a dual-mesh approach by considering three different remeshing strategies in order to reduce the computational time, at some expense of the computational accuracy, has been proposed. By applying the proposed methodology, the ring is subdivided into different sectors meshed with different criteria in order to reduce the computational time related to the sections of the ring not directly under deformation. The results of the approach are promising but the continuous remeshing required by the algorithm reduces the advantages of utilizing a coarser mesh in the region of the ring not under direct deformation.

Although several authors focused their attention on the development of analytical models for the estimation of both the radial and the axial forming force in the radial-axial ring rolling process, a general approach, which can be applied to both deformation gaps, seems to be missing. In addition to that, as also stated in the relevant works, the utilization of the model available in the literature seems to be either limited in the range of application or present deviations, in comparison to experimental results, those might be unacceptable, especially if a reasonable estimation is required already in the early stages of the manufacturing and product design process. On the other hand, although the utilization of advanced and dedicated numerical approaches can allow a reduction in the computational-time, the intrinsic iterative nature of the finite element approach does not allow any almost-real-time calculation of the solution. For this reason, if many different combinations of process parameters and different study cases are meant to be analyzed, it might result in a huge computational burden.

Following these considerations, the research work presented in this paper presents a statically determined slip line force model for the estimation of both the radial and the axial forming force in the radial-axial ring rolling process of flat rings. Based on authors' previous work, ring preform and feasible ranges for the main process parameters as well as geometry, strain, temperature and strain rate evolution during the forming process can be analytically estimated [7,4,18] and, accordingly, the forming forces are estimated throughout the process, allowing to identify both their trend as well as their maximum value. In order to enhance the understanding of the paper contents as well as the paper flow, a summary of the main results of previous authors' works is presented in Appendix A whereas the governing equations at the basis of the slip line theory are reported in Appendix B.

The proposed slip line algorithm and the developed numerical model, utilized for further investigations in the paper, have been validated by comparing their estimations with the results of laboratory experiments carried out on a laboratory-size ring rolling machine and by utilizing a Pb75–Sn25 alloy ring. In the comparison between analytical and experimental results, a maximum deviation of 1.86%, for the radial forming force, and 4.55%, for the axial forming force, has been observed. Concerning the numerical simulation, same in comparison to the relevant laboratory experiment, the maximum deviations have been identified in 6.86% and 0.88%, respectively. The validated analytical and numerical models have been applied to nine study cases where the outer diameter of the ring ranges from 800 mm and 2000 mm, resulting in maximum deviations of 4.92% and 5.88%, for the radial and axial forming forces respectively. Based on the positive results obtained both in the validation cases as well as in the wide range of study cases where the model has been applied, the proposed approach seems to be reliable for the application in both industrial and research environment, for a real-time and reasonable estimation of the forming forces.

2. Novelty of the research

The research presented in this paper provides the theoretical background and the full algorithm for the implementation of a slip line based algorithm for the estimation of the process forces in the radial-axial ring rolling process. As also highlighted in the introduction, the literature force models developed for the estimation of the radial forming force have a variable accuracy depending on the size of the ring or on the thickness reduction ratio, both of them not normally under the direct control of the process engineer. This fact has been proven in Quagliato and Berti [4] for the case of the application of the model proposed by Hawkyard et al. [2] and is included in the conclusions of the work of Parvizi et al. [5]. In addition to that, concerning the estimation of the axial forming force, only two literature contributions are available in the literature, as follows. In the work of Wang and Wang [11], no validation of the model is proposed thus the accuracy of the proposed formulation