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Development of a geometric modelling strategy for roll pass optimal design

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A B S T R A C T

Roll pass design is one of the most important tasks in shape rolling operations that are employed to provide raw materials with appropriate cross-section profiles for various industrial applications. Currently, many approaches, such as experience-based trial-and-error strategies, finite element methods, and expert systems, are applied to improve both quality and efficiency of roll pass design. However, due to lack of a flexible geometrical modelling strategy, the application of extant approaches is largely limited. This study attempts to develop a novel approach for generic geometrical modelling to support optimal design of roll passes. Features of the proposed model are analysed to support its application. Furthermore, a parameters estimation approach based on genetic algorithm is also developed to facilitate the transformation between the generic model and other geometrical models, as well as to improve its flexibility and applicability. The results from the case study presented in the paper indicate that the new model is more flexible and efficient, and that the parameters estimation approach also can achieve high transformation accuracy and efficiency.

1. Introduction

Shape rolling is an important plastic working practice that enables the manufacturing of long products of different cross-section profiles and sizes. The high productivity of rolling operations and the desirable mechanical properties of rolled products make shape rolling extensively used to provide raw materials for other industrial applications [1–4]. During shape rolling processes, the desired shape of metal is obtained through the plastic deformation occurring in-between roll groove embedded in two parallel rolls rotating in opposite directions [1,2]. Having the most influence on rolling operations, roll pass design (RPD) plays a pivotal role in the quality control of rolled work-piece and in ensuring the cost efficiency and productivity improvement of rolling operations. It is employed to schedule the rolling sequences for rolling systems and to design cross-section profiles for roll grooves applied in rolling processes [5].

Over the last decade, the acceleration of industrialisation has been boosting the global demand for high quality steel products obtained from shape rolling, placing both opportunities for and heavy burdens on steel manufacturers. To meet the challenges for productivity and quality improvement, as well as for cost efficiency, iron and steel manufacturers increasingly put emphasis on the innovation for RPD [4–6]. However, with the simultaneous spread and elongation of the rolled material in the deformation zone between two roll passes, the levels of difficulty for deformation behaviour analysis and profile prediction on rolled work-pieces can increase dramatically, making the geometric modelling for RPD highly challenging. Therefore, the improvement of efficiency, accuracy and flexibility of geometric modelling of roll pass profile becomes a major issue in the implementation of RPD.

Issues related to RPD have been investigated for centuries. A great deal of theoretical and experimental data, as well as design and operate experience are accumulated, which lead to the development of empirical rules and approximate formulae to guide geometric modelling for RPD. However, the complexity and unpredictability of metal flow in a hot rolling process makes geometric modelling more like art than science [7–9]. Therefore, to support the RPD with accurate geometric models, as well as to reduce the difficulties of modelling, a number of assumptions and simplifications have been added to create special models for some typical cases. While those models were popular in early years due to being convenient to use, their accuracy is greatly reduced by the

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application of assumptions and simplifications, and their flexibility is greatly limited due to lack of means for transformation between these models [8,10]. When designing a multi-pass rolling system, a large number of roll grooves of different shapes are involved and different approximate formulae are applied for geometric modelling. The complexity level of RPD grows significantly with the increase of the amount and types of roll passes.

The developments of three-dimensional modelling and finite element (FE) analysis techniques have promoted their applications in RPD. These methods are capable of improving the quality of geometric modelling and simulating the deformation behaviours of rolled materials with a higher accuracy. However, the efficiency and computational cost of FE simulation for nonlinear problems remain as major challenges, although there has been great advancement in computational technologies over the last two decades. Meanwhile, applying the FE model-based simulation for RPD is very restrictive, as every change in process conditions requires the development of a new simulation. Furthermore, it is difficult to have accurate settings for various aspects of deformation conditions [11–14]. In order to overcome these limitations, new approaches based on hybrid artificial intelligence-finite element (AI–FE) modelling are recently developed. For instance, Shahania et al. [15] proposed a FE-Neural Network based approach to predict influential parameters for hot rolling. The geometric and processing parameters obtained from FE simulation are used for training the artificial neural network, and then the network is employed for predicting deformation behaviours. Sanz-García et al. [16] combined genetic algorithms (GA) with FE to solve the optimisation problems for steel production processes. In their research, GA is used to adjust the parameters of the FE model until the behaviour of the material model matches the results obtained from actual experiments. Similarly, Escribano et al. [17] developed a Data Mining–FE based approach for the optimisation of skin-pass rolling. A database was firstly created based on a group of FE simulations with different materials and parameters, and then a data mining approach was used to identify the optimal predictive model, which can be used to predict variables employed in the optimal design.

In recent years, with the development of intelligent design technology, expert systems using optimisation algorithms have found increasing applications in the field of roll pass optimal design. A host of expert systems are designed to address the RPD problems. Chen et al. [18] carried out an optimal design for the ASSEL roll profile using a genetic artificial neural network. An automatic RPD method was proposed by Lambiase and Langella [19] to realise a geometric optimisation of roll passes while allowing for automation of the RPD process. The objective of the search is to find “the best” sequence with the minimal search effort [19].To avoid limitations from using single models, Abhary et al. [20] introduced a hybrid model utilising cross-disciplinary knowledge including stochastic, fuzzy, GA modelling, and process control to support the improvement of rolling system design. Meanwhile, Chen et al. [21] applied GA for rolling schedule optimisation to reduce the down time of rolling mill and to improve the flatness accuracy for rolling. Park and Anh [22] combined neural network and GA to minimise the number of passes employed in roll-forming through optimising the rolling sequence. Longitudinal strains and bulking avoidance were taken into account in the optimisation process. However, due to lack of a universal approach for geometric modelling, most of these systems employed predefined passes for the optimal design. As a result, the flexibility and applicability of extant geometric modelling methods are largely limited. It means that the complexity of roll pass optimal design using expert systems will increase significantly with the number of passes and passes types employed in the multi-pass rolling systems.

To overcome such shortcomings, this study aims to develop a universal geometric modelling strategy, with a higher flexibility and modelling efficiency, to support the RPD. Additionally, in order to use the design data accumulated in the past implementations of RPD, the proposed strategy needs to be compatible with other RPD geometrical models. Namely, it should be feasible to achieve transformations between the new universal model and other geometric models. The rest of the paper is organised as follows. Section 2 presents the formulation of the universal geometric model, as well as several typical profile curves obtained from this model for the constructions of roll grooves. Section 3 analyses the characters of the proposed model. A GA-based parameters estimation approach is developed in Section 4 to support the transformation. Section 5 presents a case study and comparative analysis to demonstrate the application and effectiveness of the model. The summary and conclusions are discussed in Section 6.

2. A universal model for RPD geometric modelling

In order to decrease the variables applied for the geometric modelling of multi-pass rolling system, a novel universal model is developed in this paper. This model consists of trigonometric function, trigonometric hyperbolic function, and exponential function components. As shown in Fig. 1, assuming the profiles of roll grooves are located in the y–z plane and symmetrical about the y-axis and the z-axis, the x-axis is parallel to the central axis of rolls and through the centre of the roll gap. The universal geometric model can be described as Eq. (1) [23]. There are five parameters (namely m, a, d, f and g) employed to construct the formula. However, only four of them are independent variables, while c is a dependant variable, and is determined by the value of m, i.e. when $m>0$, then $c=0$; otherwise $c=1$. Through adjusting the values of the four independent variables, various curves can be achieved to define the profiles for different roll passes.

$$\begin{cases} y(\mathrm{t}) = \begin{bmatrix} (1-c) & c \end{bmatrix} \times \begin{bmatrix} a\cdot(\cos(\mathrm{t}))^{(1-c)\cdot \mathrm{e}^{-f}} \\ f\cdot(\sinh(\mathrm{t}))^{c\cdot \mathrm{e}^{-a}} \end{bmatrix} \\ z(\mathrm{t}) = \begin{bmatrix} d & -g \end{bmatrix} \times \begin{bmatrix} \left[\sin\left[\mathrm{t}^{(2\cdot \mathrm{e}^{-m^2})}\right]\right]^{(1-c)\cdot \mathrm{e}^{-f}} \\ \left[\cosh\left[\mathrm{t}^{(2\cdot \mathrm{e}^{-m^2})}\right]\right]^{c\cdot \mathrm{e}^{-a}} \end{bmatrix} \end{cases} \quad (1)$$

As this model is established for designing symmetrical roll passes whose cross-section curves are symmetrical about both the y- and z-axes, thus only 1/4 profile curves of roll grooves are discussed to simplify the analysis. Thus, the interval of parameter t is set as

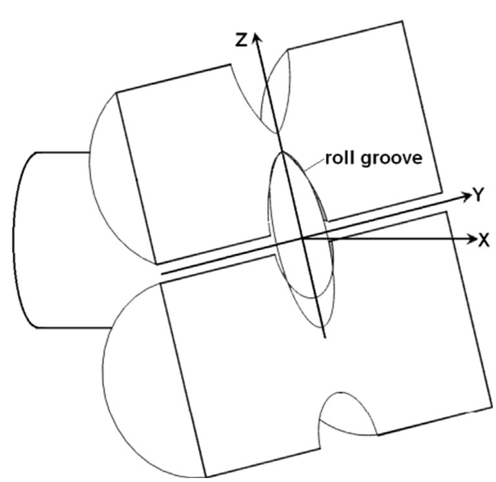

Fig. 1. The coordinate system used for modelling.