

A Knowledge Based Hybrid Model for Improving Manufacturing System in Rolling Mills

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Abstract. Hot steel rolling is amongst the most important industrial techniques because of huge amount of consumed resources, immense environmental impact, and the significance and enormous quantity of long products. Criteria for improving rolling operations include process efficiency, resource consumption, system reliability, product quality and ergo-ecological sustainability. There is an increasing availability of information within and beyond the domain of forming by rolling. With advances in computerised information processing, it becomes apparent that further progress is to be sought in intelligently combining the strategies and theories developed in differing disciplines. The key to optimising rolling systems is to be found in hybrid models. This approach calls for utilising cross-disciplinary knowledge, including a selection amongst methods such as stochastic, fuzzy and genetic modelling, process control and optimisation as well as supply chain and maintenance management. Evidence obtained by experiments using small-scale chemo-physical modelling encourages the use laboratory rolling for preliminary validations. Research strategy is conceptualised on the basis of a knowledge-based hybrid model. The sample space for this model is constituted by the rolling passes translated into the form of vectors. An example of a rolling pass translation into the vector form is presented.

Introduction

Hot steel rolling (hereafter: rolling) is one of the most important and most efficient processes in modern manufacturing since it involves large-scale man-made systems that modify quality of an immense volume of steel and consume a proportional amount of resources. In particular, ergonomic issues and environmental sustainability (pollution and energy emissions) have become critical.

Numerous publications treat aspects of rolling, and a huge database has been accumulated in the industrial systems. Yet even a limited review of literature [1-10] provides abundant evidence to the need for further optimising the rolling systems in line with the philosophy of continuous improvements, and indeed in line with the current calls for more rational use of global resources.

Research that will address the above issues requires mobilising the resources which exceed capacity of a single method and an isolated academic discipline. Hence we propose that a hybrid approach has a better chance of bringing about prospective improvements.

A cross-disciplinary approach involving disciplines ranging from mechanical metallurgy and plastic forming of steels to the applied mathematical statistics and system control, has to be employed. Balanced collaboration across this spectrum will integrate various intelligent techniques with appropriate computational methods. While most of the approaches concentrate on a specialised-domain-knowledge, this approach builds on the idea that each specialty has something to offer, and when combined they can provide more reliable solutions. A challenge is how to

mobilise and integrate cross-disciplinary knowledge that combines suitable methods such as process modelling & control and operations optimisation & scheduling.

Problem Description

The actual practice of rolling production continues to outstrip our theoretical understanding of it [5]. This means that expensive corrections and trials must be undertaken at the resource consuming industrial scale.

Various deterministic methods, such as finite element/difference modelling [6-8] and slip-line-fields [9] continue to be used in attempt to optimise the process within the deformation zone. These methods alone cannot provide sufficient shift in the optimisation effects; a combination with other “competing” approaches is needed. Applications of hybrid models for hot rolling are already published [1,10], but still fall short of obtaining sufficiently optimised roll pass design implementations over a suitable time.

Concepts based on the assumed or deterministically calculated values of variables such as friction coefficient and temperature do not provide sufficiently optimised dimensions for actual roll grooves. In the process of rolling, where most factors not only vary across subsequent passes, but also fluctuate during the course of the production series, it appears that a stochastic approach is a *conditio sine qua non*.

Optimisation of rolling, providing that process is void of catastrophic interruptions (such as appearance of cracks and tool fracture), can be evaluated on the basis of the following norms:

(i) yield, (ii) productivity, (iii) reliability and (iv) costs.

Ideally, hot solid steel should plastically flow through a sequence of passes in such way to maintain an optimal level in all indicators. More detailed analysis leads to the recognition of factors such as rolling pressure, temperature, rolling and sliding velocity and tool life. All these variables are significantly affected by the phenomena embodied within the deformation zone which, in turn, is substantially influenced by the roll pass design.

Research Strategy

Published research into roll pass design, rolling operations and maintenance of rolls do not take sufficient advantage of data accumulated in published sources, by the rolling mill operators and by the roll manufacturers. Industrial and scholarly classified databases can be analysed using a special hybrid approach that combines stochastic modeling with other modelling strategies, and advanced knowledge processing methods.

The minimum intent is to derive a model which can be used in a decision support system for the roll pass (re)design which can be further optimised by means of corrections during the operations and maintenance in an industrial rolling mill. Rolling mill line can be viewed as a supply chain system with the rolls as the key assets, and a principal factor in optimisation. In particular, roll grooves present the critical nodes, and the focus in this research is on the groove geometry.

A roll groove meridian is the intersection curve between the revolution surface and a plane through the revolution axis. Meridians which define the two-dimensional geometry of roll grooves can be translated into appropriate vectors. Generic functions can be used to translate a broad spectrum of pass geometries into 15-component vectors. Once this is achieved, statistical analysis of the resulting vector series can be conducted to extract the roll pass design interdependences based on many observations of industrially realised rolling sequences.

This will enable intelligent anticipation of the roll pass design by means of identifying the boundaries of possible groove geometries. Such information can be used to calibrate promising trials at commencement of new mills and/or profiles, to optimise existing schedules, to define emergency roll pass design routes, to modify real-time roll pressures to compensate for sudden or gradual changes in processing, etc.

The above research strategy will be depicted on the example of roll pass design for rolling round wire and rods. In this case, the presence of straight line segments in the groove meridians is, in most

cases, just a consequence of historical fashions in technical drawing practice and the inertia in deriving the section transformations departing from the initial cuboid. These line segments change into curves by the effect of continuous wear during the rolling process.

In order to maximise norms (i)-(iii) and minimise norm (iv) defined above, the rolling sequence should be optimised. Roll pass design is one of the key factors in this task.

Each groove should be designed by propitious selection of osculating curves, rather than involving straight lines. This process should start with the final pass. If the material for the finishing roll and the rolling draft are selected appropriately, the continuous wear will produce a constantly, or even increasingly, smooth surface. With this in mind, an advantage could then be taken of the relationship between the groove wear and the two-dimensional geometric tolerances, to extend the tool (roll) life.

For example the circularity and the dimensional tolerances of the final groove can be designed to fit the extreme limits of the product tolerances, with balancing the future wear to work out the groove surfaces towards the opposite extreme of the product geometrical tolerances.

This can be achieved by understanding the complete wear path (route) i.e. the change from a new-dressed groove to fully worn groove geometry.

When designing the penultimate pass, additional knowledge is required along with defining the wear path: there is a need to understand the full range of possible geometries that can be selected for the penultimate grooves. Based on this, the penultimate pass is designed to direct its wear from one extreme (a shape that still allows for rolling into a satisfactory final product within the finishing pass) towards the opposite extreme, which still allows for successful rolling of the final product.

This procedure is repeated in a step-by-step design procedure to design the grooves for all remaining transiting passes to be used for rolling of the initial cuboids into the final products.

Current results

Rolling sliding contact distance (L), one of principal factors in roll wear, is defined in [2, 3]

$$dL / ds = N \cdot u / v_R \quad (1)$$

N = total number of roll revolutions while in contact with hot steel

s = deformation zone length (mm)

v_R = roll peripheral speed (mm/s)

u = sliding velocity along the interface tool-rolled material, (mm/s); **u** = f(s)

The change in the groove surface roughness was reported in [11]. It was observed that the surface roughness remained constant or even decreased with the increase in the rolling sliding contact distance L. Detrimental increase in the roughness occurred only in the final stage when groove life was near to an end due to cumulative symptoms of the wear modes.

The limits (boundaries) of the groove meridians for newly introduced rolling sequence are affected by the following aims:

(a) ensuring that an eventual correction of the meridian geometry can be physically realised, i.e. selecting such groove geometry for the first trial as to preserve a possibility of a subsequent correction by machining the same roll at a zero or minimum decrease in roll diameter;

(b) ensuring that the product is obtained within the tolerances with finishing grooves designed within an extreme which will be worn out smoothly during the rolling process, thus acquiring the geometry that converges towards the other extreme of the groove geometry.

Extensive research [12-15] provides ample evidence that achieving the first tasks (a) is enhanced by laboratory experiments using lead models. The authors of this publication have verified a number of industrial roll pass design projects using this method.

In order to achieve the second aim, (b), knowledge of the meridian wear trend should be combined with the understanding where the extreme boundaries of the possible geometries are positioned. For example, in case of the final pass, the extreme boundaries of possible geometries are

defined by geometric tolerances of the final product. By understanding how the wear of meridians will develop, the design can be made to counterbalance and slow down the process of the meridian change. Figure 1 presents one such design of the final pass for rolling $\varnothing 12$ mm:

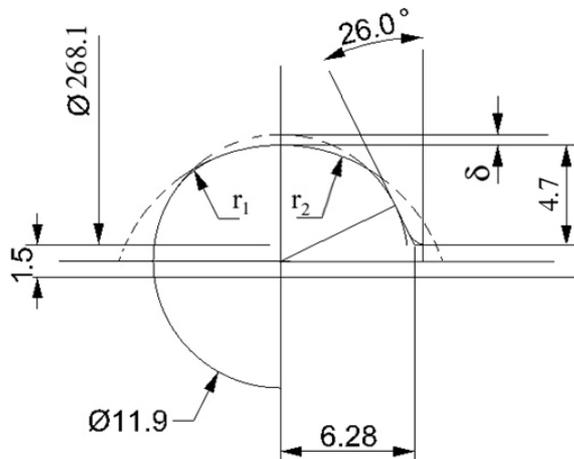


Fig. 1 Final pass grooves for rolling rounds $\varnothing 12$ mm

Since the maximum wear (δ) will develop symmetrically starting from the vertical axis of the symmetry, radius $r_2 > 6$ is introduced to take advantage of the allowed deviation from the product cross-section circularity. In addition, the overall groove diameter ($\varnothing 11.9$ mm) is designed to take advantage of the dimensional minus tolerance, bearing in mind that this is the horizontal dimension the product will have at the finishing temperature (e.g. 800 – 900 °C).

In order to direct the maximum wear away from the meridian segment around the zone characterised by the 26° slope (Fig 1), the sliding distance L in that zone should approach zero.

Monitoring and control of the sliding velocity should be linked to sensors for online detecting the wear development. Roll maintenance should take advantage of understanding the limits of the possible groove geometries. Further optimisation can be achieved by designing the maximum drafts and wear at the initial passes, and by minimising the draft at the final pass. Two semi-finishing passes should be introduced, where the first semi-finishing pass will bear most of the draft.

The school for Advanced Manufacturing and Mechanical Engineering at the University of South Australia currently invests in an investigation of mathematical transformations for obtaining analytical expressions for the groove meridians. For the case of rolling wire, analytical form is currently developed that allows for translating the meridian into 15-component vectors, K_{ij} .

$$i = 1, 2, 3, \dots, 12$$

j = rolling pass identification, e.g. $j = 0$ denotes the final pass; $j = 1$ denotes penult pass, etc.

For the ranges of indexes $i = 1$ to 4 ($i = 5$ to 9) K_{ij} present the coefficients of the first (and second) osculating curve, respectively.

K_{10j} = value of the x coordinate within the deformation zone exit plane at the point where the groove meridian and the workpiece cross-section meridian become separated.

K_{11j} = roll diameter at $x = 0$ ($x =$ abscissa).

K_{12j} = maximum content of carbon equivalent in the rolled steel.

For example, for the case of the grooves shown in Fig 1 without taking into account radii r_1 , r_2 and the offset δ , the meridian vector is:

$$K_{i0} = (0.000; -1.000; 1.000; 0.000; 1.000; 5.980; 11.13; 1.629; -1.000; 4.107; 1.206; 3.900; 6.010; 268.04; 0.260)$$

And the meridian vector with taking into account $r_1 = 8$ mm, $r_2 = 4.5$ mm and $\delta = 0.5$ mm is:

$$K_{i0} = (-2.400; -1.000; 1.001; 0.000; 1.010; 7.881; 11.20; 1.400; -1.350; 4.50; 1.221; 4.800; 6.010; 269.04; 0.260)$$

Further minimisation of the count of the vector components below 15 is sought for by virtue of computerised analytical geometry and genetic algorithms. The problem of minimising the count of vector components is important because this affects the limits of the confidence intervals.

Such vectors allow for real-time statistical analysis of published roll pass sequences thus pointing at the extreme options of possible groove geometries for a series of rolling passes. A

regression equation can be estimated using data from published pass sequences, and the mill operation and roll maintenance data base. Regression equation confidence limits depend on the counts of the observations and the independent variables (vector components). These confidence limits will be used to define the boundaries for possible groove meridians. A reverse transformation of the components K_{ij} into pass technical drawings involves application of the fuzzy logic.

Groove meridians should be located within the confidence intervals to anticipate the further wear and maintenance induced changes within a still plausible zone. This will be enhanced when the roll maintenance data base is added to the sample space used for the roll pass design statistical analysis.

An example of a regression model obtained by analysis of pass geometry for hot rolling of plane-carbon round wire into flat sections (Fig 2) has shown the following statistics:

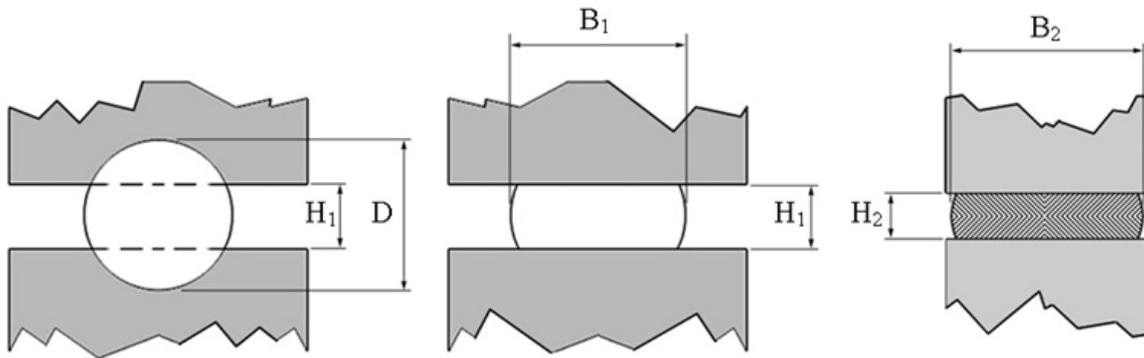


Fig. 2 Geometry of the final passes

Finishing pass roll radius: $R_1 = 80$ mm; penultimate pass roll radius: $R_2 = 130$ mm.
 Entry wire dimensions: $6 \text{ mm} < D < 18 \text{ mm}$. Entry temperatures: $1000 \text{ }^\circ\text{C} \pm 20 \text{ }^\circ\text{C}$.
 Exit dimensions of flat bar: $2 \text{ mm} < H_2 < 7 \text{ mm}$; $2 < (B_2/H_2) < 9$.

$$B_2 = 7.345 + 3.231D - 5.862H_2 - 0.052D^2 + 0.412H_2^2 - 1.22D/H_2 \quad (2)$$

$$(H_1 - H_2) < \left[0.25 \cdot (B_1 + B_2)^2 / R_2 \right] \quad (3)$$

$$(B_1 + B_2) \cdot (B_1 - B_2)^{-1} = (H_1 + H_2) \cdot \left[1 + 0.25 \cdot (1 + \alpha) \cdot (B_1 + B_2)^2 / (\alpha \cdot R_2)^2 \right] \cdot (H_1 - H_2)^{-1} \quad (4)$$

$$\alpha = \arccos \left[1 - 0.5(H_1 - H_2) / R_2 \right] \quad (5)$$

The goodness of fit $R^2 = 0.96$ and the standard error is 0.35 mm at the confidence level of 95%.

Conclusions

Anthropogenic consumption and harmful emission reductions require intelligent technological changes in the major industrial processes. This prompts for application of knowledge based models to improve systems such as hot steel rolling mills. Steel manufacturing consumes enormous resources, for example the industrial water requirements include over 4 tonnes of water for 1 tonne of steel [16].

This requires a cross-disciplinary approach involving fields such as mechanical metallurgy, plastic forming of steels, mathematical statistics, operations research and system control. Hybrid amalgamation across this spectrum will integrate various intelligent techniques with appropriate computational methods. A challenge is how to mobilise and integrate cross-disciplinary knowledge that combines suitable methods such as process modelling & control and operations optimisation & scheduling. Accelerated use of hybrid knowledge is more effective compared to isolated theories which do not take advantage of competing models.

Industrial and scholarly accumulated databases of rolling pass schedules can be analysed statistically to extract stochastic models. The accumulated empirical and theoretical knowledge and the giant leaps in process control and information technology allow for further optimising the hot rolling operations both off- and on-line.

A unifying hybrid model is sought for which will take into account a sufficient number of the variables and factors, and which will optimise the rolling process by means of online monitoring of the total system. Rolling mills of the 21st century must focus on flexibility, productivity, quality and sustainability. The expected benefits include the following:

- the rolling process will become more stable (more reliable); adjustment interventions will become less frequent and pass adjusting time will decrease,
- overall life of rolls will increase, the depth of necessary redressing of rolls will decrease,
- rolling process energy and other resource consumption will decrease,
- manufacturing process yield, productivity and reliability will increase,
- production costs will decrease,
- working range for sequences and series of two-plane-symmetrical grooves will improve,
- the ecological and ergonomic sustainability of the overall process will improve.

References

- [1] H.J. Kim, M. Mahfouf and Y.Y. Yang: *Journ. of Mat. Processing Techn.*, Vol. 201/1–3 (2008), p.101
- [2] S. Spuzic: *Hot Rolling Mill Roll Wear - Some Aspects of High Temperature Abrasion* (Ph.D Thesis, The University of South Australia, 1996).
- [3] S. Spuzic, M. Zec, K. Abhary, R. Ghomashchi and I. Reid: *Wear*, Vol. 212, Issue 1 (1997), p.131
- [4] C. Eriksson: *Journ. of Mat. Processing Techn.* Vol. 174, Issues 1-3 (2006), p.250
- [5] W. L. Roberts: *Hot Rolling of Steel* (CRC Press, UK 1983).
- [6] S.M. Byon, D.H. Na and Y.Lee: *Journal of Materials Processing Technology* Vol. 209, Issue 9 (2009), p.4465
- [7] S.Y. Yuan, L.W. Zhang, S.L. Liao, G.D. Jiang, Y.S. Yu and M. Qi: *Journal of Materials Processing Technology* Vol. 209, Issue 6 (2009), p.2760
- [8] H.-C. Kwon, H.-W. Lee, H.-Y. Kim, Y.-T. Im, H.-D. Park and D.-L. Lee: *Journal of Materials Processing Technology* Vol. 209, Issue 9 (2009), p.4476
- [9] K. Klarin, J.-P. Mouton and S.-E. Lundberg: *Journal of Materials Processing Technology* Vol. 36 (1993), p.427
- [10] J. Zhao, W. Wang, Q. Liu, Z. Wang and P. Shi: *Control Engineering Practice* Vol. 17, Issue 6 (2009), p.629
- [11] S. Spuzic, M. Abdulsamad and M. Khraisheh: *Research report LGP 3-16* (King Abdulaziz City for Science & Technology, Saudi Arabia 2002).
- [12] T. Kohno, in: *Proceedings the 93rd Symposium on Elasticity in Metal Processing* (1980)
- [13] N.R. Chikara and G. M. Hardy: *Int. J. Mech. Sci.* Vol 1 (1977), p.575
- [14] W.-S. Fun: *The Use of Lead for Simulating the Hot Rolling of Steel* (MSc Thesis, Monash University, Australia 1989).
- [15] K. Garner and S. Spuzic's work on the simulation of hot steel rolling using lead samples at room temperatures; BHP Steel Whyalla Rolling Mills and Melbourne Research Laboratories 1992
- [16] G. Haughton and C. Hunter: *Sustainable Cities* (Routledge Taylor & Francis Group, UK 2003).