Software and hardware developments for innovative mill design

Rolling models serve as the theoretical foundation of mill design. Two basic models – the force model and the crown/shape model – dominate the major tasks of mill design. Mill optimisation of pass schedule crown distribution, roll profile determination and online actuator set points have been developed, applying basic models and the weighted least-square method. A balanced development of hardware and software is key to optimal mill performance.

Modern rolling mill designs go back to the 1960s. Since then, continuous improvement of mechanical components, electrical circuits and intelligent controls have been developed to improve mill performance, while reducing initial and operational costs. For instance, the hydraulic automatic gauge control (HAGC) system was developed in the early 1960s after the introduction of the servo system, and further improvements made quarter gauge tolerances possible. The work roll bending system was initiated at about the same time to improve strip crown and shape quality.

Later, development of various crown/shape actuators, together with sophisticated mathematical models, led to better quality strip, improved production and increased yield. The motor-generator set for mill speed control was replaced by thyristor drives, and the AC drive motor and digital PLC reduced maintenance costs and promoted system response.

Mill types became more versatile for special rolling purposes, including 2-hi, 4-hi, 6-hi, z-hi, and cluster mills with various roll configurations. Common protocols, network systems, information sharing and fault detection/fallback systems, provided flexibility, agility and adaptability of the control system to smooth mill operation.

On the other hand, thanks to profound software and model developments, basic rolling theories were developed, and associated equations were solved numerically to support and stimulate novel mill hardware designs. Many mathematical models were generated and published in the literature, such as the force model, the crown/shape mode, rolling mill optimisation, the pass schedule model and the mill design model.

The modern mill design embraces design innovation and model advances. As shown in Figure 1, two tasks develop separately, and yet they are dependent on each other for better performance of future mills. A mill design will be initiated by the steel producer with requirements of the product mix, annual production and the target quality identified. The software/hardware ‘design loop’ determines a proposed mill to meet the requirement at the proposal stage. It then works with the mechanical/electrical design tool to finalise the mill design at the design stage. The software package becomes the basis of the level-2 control system to interact with the mill and the information system at the operating stage.

This article describes recent developments of hardware and software. It will introduce advanced rolling models first and then the mill design with new concepts, new looks and new features on basic conventional mills. The model initiates the mill design, which inspires further development of the model. It is worthy of discussing mutual advantages by considering innovative designs and advanced models simultaneously.
HARDWARE AND SOFTWARE DEVELOPMENT FOR ROLLING MILLS

There are four stages of development. As shown in Figure 2, the first stage is the proposal stage, which generates a preliminary mill design using a given product mix and quality. The pass design model is applied to ensure rolling feasibility with the selected work roll diameter. A smaller work roll can roll down to thinner gauges with less rolling force and power. The small work roll introduces large Hertzian contact stress as well as greater vertical and horizontal roll deflection. The back-up roll resolve model is then used to determine the optimal back-up roll diameter using the weighted cost function of natural crown performance and the fiscal cost of the roll. The mill type (from 2-hi to multi-hi cluster mills) can be determined using the roll slippage model or the simple roll diameter ratio method. The pass design model also estimates the required work roll bending force and the roll crowns according to the final pass schedule. The calculated results are passed to the mill design model, which determines the stroke and bore diameter of all cylinders, selects the roll bearings from the database, performs roll chock design and provides the preliminary mill window.

This preliminary mill design can be used to generate an initial proposal and this stage depends more on software computing results than mill hardware designs.

The design stage starts after confirmation of the mill order. This stage focuses more on the hardware design with assistance from design-related models, such as the mill modulus model, the thermal/wear model, the compressive yield stress model and the hydraulic system response model. The roll profiles can be optimised after the capabilities of crown control devices are finalised. Since the model results cannot reflect the actual mill operation, the primary purpose of the third stage is to collect real-time rolling data to tune the models. The rolling data can be used to confirm the design parameters, such as energy, lubrication, roll and roll bearing consumptions. The level-2 model in the operating stage is designed mainly to interact with the level-1 control system, the level-3 information system and the operator via the human-machine interface (HMI). The L2 model includes the pass schedule model (for force set up), the crown/shape control model (for set points of crown control devices), the tuning and learning model, and other associated programs to perform various tasks, such as data communication (L1, L3 and L2 computers), report generation (for management), and screen display (for the operator).

DEVELOPMENT OF FORCE MODELS

Rolling theories focus on the rolling force model, which is the basis of all other models. This model calculates the rolling force, the rolling torque and the rolling power for rolling parameters such as entry/exit gauges, entry/exit...
tension, work roll diameter, rolling speed, material strength and friction coefficient. It determines the rollability of the given product since the rolling schedule must satisfy the requirement of friction hill, as shown in Figure 3a. Certain rolling conditions will lead to no friction hill, leading to no roll; for instance, the large work roll for the ultra thin gauge, a large reduction with insufficient lubrication and high strength material with small exit tension.

In general, the roll bite comprises the elastic deformation zone, the plastic deformation zone and the elastic recovery zone. Von Karman’s rolling equation is applicable for all three zones since it was derived from the force equilibrium condition. The author has developed a numerical solution for von Karman’s equation. The relationship between the normal compressive stress and the normal strain follows Hook’s law in the elastic deformation and recovery zones. Von Mises and Tresca yield criteria are applied to the slip and the stick friction areas of the plastic deformation zone, respectively. The contact arc comprises the overall work roll flattening contour (a quasi-elliptic curve) and the local roll indentation. An iterative loop is needed to obtain the convergent force result by solving the von Karman equation numerically for the non-circular contact arc and various zones with different characteristics.

**STRIP CROWN AND SHAPE MODEL**

Shonet and Townsend proposed a method to divide the roll and strip into many small segments. The roll deflection of each segment can be calculated using the given force distribution on the work roll and strip interface. The compatibility equation is then applied to check the contact condition of each segment and a new force distribution is obtained. Continuing the iteration loop leads to a stable force distribution and solves the strip profile. The method was further modified into a spring-beam-gap system to eliminate the iteration loop for fast solution. The spring-beam-gap model was later improved using the two-stage transport matrix method, as shown in Figure 4a. Recent development of bi-direction two-stage transport matrix method (Figure 5b) cuts the transport time in half and minimises computing time so much that the model can also be for online application.

Strip shape can be calculated after obtaining the strip profile distribution from the above crown model. The exit tension distribution is the shape of the exit strip. The mass flow rule can be used to calculate the exit length of each segment, since the entry shape is given and the length distribution can be used to find the individual tensile stress of each segment. The integration of the exit tensile stress over the width is the applied tension force. An iteration loop is needed to adjust the strip spring constant of the crown model until the tensile stress distribution is stabilised. Without considering the entry crown, the bottom picture of Figure 4 shows the strip crown for a 6-high mill in four rolling conditions (no crown control, 20 work roll bending, 40 t intermediate roll bending and intermediate roll shift to strip edge) with various strip widths (5” to 28”) and strip moduli (1,000~5,000ksi).

**PASS AND MILL DESIGN MODELS**

The pass design model was developed on the basis of the force model with a pass design algorithm to process the given product from the entry to the delivery thickness. It is a rule-based model and the total passes are categorised into three pass groups – the payoff group, the intermediate group and the finishing group. The pass numbers of the payoff and finishing groups can be specified by the user, and the remainder belong to the intermediate group. The model adjusts the pass group internally if the total passes do not meet the assigned pass numbers of all three groups.
Each pass group possesses particular rules, including the reduction rule (max/min % reduction, max/min draft, max bite angle), the force rule (max rolling force, max force per unit width), the tension rule (max/min exit/entry tension ratio, ratio of tensile stress to work hardening stress, overall max tensile stress), the friction coefficient rule (friction equation or constant friction coefficient), the operation rule (pass type, pass/coil interval times, min run time), various optional rules (selected force models, roll flattening equations, reducing crown trend), and the mill specification (available power of main/reel/payoff drive, top/base speed, overload ratio, roll dimensions, coil weight, coil PIW (lbs per inch width)).

The pass design model generates the pass schedule based on those assigned rules. The pass design model generates four reports – the summary, the detailed schedule, the strip crown effect and the simplified friction hill. Figure 5a shows the simplified friction hill for six passes from a particular pass schedule. The approximate roll gap (or strip thickness) profiles shown in Figure 5b are combined profiles of roll flattening and roll indentation.

The calculation results from the pass design model are fully transferred to the mill design model. There are eight tasks performed by the mill design model:

- Select roll bearings using database query from the established bearing database
- Estimate the roll bearing life using the accumulative damage method and bearing L10 life
- Calculate and check the roll contact stress using Hertzian equation
- Determine roll material using the calculated combined principal stress at the roll neck
- Design roll chocks and the rolls based on selected bearings and required strip width range
- Size bending cylinders based on preset hydraulic pressure and calculated bending forces
- Calculate the strokes for roll positions (minimum rolls, maximum rolls, and roll change), and
- Plot a rough window layout of three roll positions as shown in Figure 5c.

The mill design model, which integrates all engineering steps (from pass schedule to window layout) into an advanced program, shortens the design time and provides a consistent design procedure for design engineers.

**TASK MODELS AND PROBLEM SOLVING**

Task models are generated particularly to solve specific rolling problems and/or to be a sub-model of the major level-2 model. They may or may not directly relate to the mill design.
Task models related to the mill design include back up roll determination model, roll configuration model (cluster mill), optimal mill housing model, roll slippage model, winder design model and other miscellaneous models. Task models not directly related to the mill design includes thermal crown model, roll wear model, strip cooling model, optimal roll profile model, hydraulic system response model, torsion amplification model, mill dynamic response model, component life expectancy model, chatter vibration model, strip damping model, stress curve tuning model and force/speed/crown/shape learning models. Detailed discussion of various models can be found elsewhere in the literature.

MILL DESIGN – HARDWARE INNOVATION

As mentioned before, hardware development must accompany advanced software. Results from software calculations support the hardware design. This section is used to describe a typical example of hardware design with software assistances on many aspects using an example of a newly designed reversing 6-hi rolling mill with various features whose capacities are calculated by the software models.

Mill overview

The reversing 6-hi mill as shown in Figure 6, has been designed to roll high strength carbon steel with a large entry/exit gauge (5-0.07mm) and width range (600-1,250mm). The roll sizes, roll bending forces, and shifting features are determined by the pass and mill design model. The mill is equipped with a bottom mounted hydraulic AGC cylinder, work and intermediate roll bending, intermediate roll lateral shifting, top mounted pass line adjustment wedge and roll changing device. The hydraulic response is studied by the hydraulic response model and the piping system is designed based on the study results. Work rolls are driven by two AC motors through a gear reducer pinion stand. The roll materials are determined by the combined bending and shear stress calculated from the mill design model. The mill is furnished with the AGC and automatic flatness control (AFC) systems. The related models are applied to consider rolling feasibility, roll contact stress, bearing life, strip temperature, thermal crowns, crown effects due to roll bending and roll shifting, and other rolling parameters.

Drive and lubrication system

This mill is designed to be a work roll-driven mill, although it can be driven by other rolls depending on the stress level and special purposes. Upper and lower work rolls are driven by two variable speed AC motors through a gear reducer. The main drive motor power is determined by the pass design model, the product mix, and desired rolling speed. All gears are heat treated alloy steel and rotate in anti-friction bearings. The gearbox and the motor size are optimised to minimise the overall cost, while providing the required rolling torque. Lubrication comes from the central lubrication station. Drive spindles are of universal joint type. Hydraulically activated spindle support is applied on the drive side of the mill to hold the spindles during roll change.

AGC hydraulic force cylinders

Hydraulic force cylinders mounted at the bottom of the housing can exert a separating force according to the requirement from the pass schedule. They are controlled by servo valves with precision digital position encoders. Control features include AGC, tilt control and mill modulus calibration for both manual and automatic operation. The system consists of all required logic boards, joysticks, instrumentations, digital displays for roll positions in an increment of 0.001mm, and digital bar graphs for total and differential mill rolling force. The rapid open system opens the roll gap automatically to a pre-determined position when an E stop is activated to reduce damage to the mill and rolls.

Roll bending and shifting

Positive and negative bending of work rolls and intermediate rolls are accomplished via pistons built into four Mae West blocks. Each block includes double acting hydraulic pistons controlled by proportional pressure valve for bending both sets of work rolls and intermediate rolls towards or away from the strip (positive or negative bending). Crown effects due to the roll bender are determined by the crown/shape control model for various strip widths, strip modulus, roll...
shifting positions and work roll diameter. Roll bending controls are located in the main desk and arranged for simultaneous adjustment on drive or operator sides. Mae West blocks also include double acting hydraulic pistons for counterbalance of the upper back-up roll assembly. The intermediate roll shifting device is operated hydraulically. Top and bottom roll chocks are engaged with Mae West blocks, which are mounted on the shifting mechanism operated by two hydraulic cylinders mounted on the drive side of the housing. Top and bottom intermediate rolls are shifted in opposite directions to compensate crown variations of various product mixes. Eight cylinders are incorporated into the steel blocks and provide positive and negative roll bending. The extreme position of the cylinder is to line up the rails in the mill for roll changer (see below). Hydraulically operated chock keepers are built into this shifting mechanism.

Passline adjustment The pass line adjustment device is mounted at the top of the mill housing and is designed as a step-wedge arrangement device operated by two hydraulic cylinders. This design can maintain the pass line and allow wide roll gap opening during roll change. After the operator enters the roll diameters, the system automatically positions the step and the wedge to maintain the pass line. Four steps provide coarse adjustment and wedges provide fine adjustment within all required ranges. This type of arrangement can minimise the space requirement.

Back-up roll changer The roll changer cart is used to remove and insert back-up rolls. The roll changer runs on rails mounted in the foundations in front of the mill and is driven by two hydraulic motors. Matching rails between the front and rear mill housings allow the back-up roll assemblies to be moved into or out of the mill housing.

The first step to remove the back-up roll assembly is to remove the work rolls and intermediate rolls, then the roll changer is positioned next to the mill. The hook from the roll changer is then engaged with the operator side chock of the lower back-up roll, which is pulled out so as to place a roll spacer on the top of the lower back-up roll. The bottom back-up roll, together with the spacer, is pushed back to the mill. Since the work and intermediate rolls are already out of the mill, the pass line has already been lowered. The assembly can then rest in a fixed position to allow the upper back-up roll assembly to lower down and sit on the spacer after retracting the keepers of the upper back-up roll hydraulically. The entire back-up roll assembly is pulled out of the mill by the hydraulically operated push/pull roll changer cart. The assembly is then lifted and transported to the roll shop and the new assembly is placed on the rail in front of the mill. The push/pull cart then pushes the new back-up roll assembly into the mill. The upper back-up roll assembly is lifted by counterbalance cylinders, the pass line is adjusted, the roll chock keepers are engaged and the mill is ready for next operation.

Quick WR/IR changer This quick changer device is designed to change the work roll assembly and/or the intermediate roll simultaneously. The quick roll changer consists of a self-propelled lower carriage that runs on rails mounted in the floor. An upper side shift table, a changing head (shuttle), and hydraulic/electrical motors drive the changer wheels to move the assembly to and from the mill. A single hydraulic cylinder indexes the side shifting table horizontally between the load and unload positions and a hydraulic motor traverses a changing head for removal and installation of the roll assemblies. The side shifting table has two bays, one is loaded with new roll assemblies and the other is empty to receive used rolls from the mill.

CONCLUSIONS

This paper has demonstrated that the innovative mill design originates from the novel hardware design concept and the supporting software results. The hardware design relies on the modern 3D design tool and the software programs rely on derived mathematical models. With modern high-speed computing devices, the software can process many routine design works rapidly, and with fewer human errors. The software design can cover not only sophisticated mathematical models, but also simple tasks, such as drawing search and summary of bill of materials. Some standard routines which consume many manhours can be fulfilled by the software.

Obviously, the more the design procedure is standardised, the faster the mill can be designed. Engagement of the software programs and the hardware design should be pursued simultaneously to take advantages of both aspects. Modern design software promotes the parametric design which applies the pre-defined parameters and builds up the entire 3D mechanical embodiment. Software development will build on the intelligence of software models to size the mill, to produce pre-defined parameters for the mill and to generate the customised documents. Similarly, the hardware design should be based on parametric design so that the preliminary design of the mill can materialise as soon as the software model can provide those pre-defined parameters. This integration of hardware and software designs should have a major impact on design cost.

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