Computer-aided design of rolling mills

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Abstract. Computers have been used for design of rolling mills since 1960s. Easy access to high speed digital computers has facilitated use of more accurate rolling theories for design work and comprehensive computer simulations have been developed for all types of mills. These simulations include optimization of roll pass sequence, calculation of roll force, torque and temperature and detailed time studies for productivity calculations. These aspects of mill simulation are examined with specific examples.

In the design of rolling mills equipment, computer-aided design has been widely used. The available software, which covers both steady state and dynamic analysis of items such as mill stands, drive systems, manipulators, cooling beds, roll cooling, and automatic gauge control systems, is reviewed with special reference to the nature of analysis and range of applications.

Computer drafting is being increasingly used by rolling mills designers for both interactive and non-interactive applications. The integration of computer graphics with the design software holds promise for improving the productivity and creativity of designers and is an active area of development in rolling mills design organizations. A specific application where such integration has been achieved is discussed.

Keywords. Computer-aided design; rolling mills; computer drafting; computer simulation

1. Introduction

Mathematical modelling and computer simulation are being widely used today both for design and control of rolling mills. Many of the complex phenomena involved in the rolling process can be understood and quantified only with the help of computer models. Computer simulation is also used to accurately predict the effect of variations in rolling process on the mill design and for optimization studies.

The earliest attempt to develop a mathematical model of the rolling process dates back to the pioneering works of Siebel (1924) and von Karman (1925). By the end of the 1950s substantial theoretical work had been done and many design methods developed. Much of the impetus for this work came from designers and builders of rolling mills. Before undertaking the detailed design of a mill it is a normal practice to compute rolling schedules to properly size the mill for a specific application. The rolling schedule shows the nature and magnitude of forces, torques and power parameters required to reduce metal of a given stock size to the final finish size. These parameters depend on the size of the mill, the reduction pattern adopted and the other conditions of rolling such as temperature, speed, tension, roll coolant etc. It is usual to evaluate several alternatives in terms of their suitability for customer requirements.

The high volume of work involved together with the complexity of various calculations has led to the widespread use of computer methods in almost every phase of rolling mills design. The present day applications of computer-aided design (CAD) may be broadly grouped into (i) simulation models for specific types of mills and (ii) programs for detailed analysis and design of individual equipment. In most of the

leading design organizations dealing with rolling mills, computer drafting is being gradually integrated with the design software.

2. Mill simulation

In the design of a new rolling mill the starting point is a mill simulation program for the specific type of mill i.e. slabbing and blooming mill, billet, bar and section mill, rod mill, plate mill, hot strip mill, single stand reversing and non-reversing cold mill, fully continuous tandem cold mill and skin pass mill. Broadly speaking all mill simulation programs consist of three parts for: (a) calculating the pass sequence (b) computing the roll separating force, torque and power required and (c) a time study for evaluating the productivity. Temperature calculations are also an integral part of (a) and (b) above in the simulation of hot rolling mills. These calculations constitute interacting loops that are intimately related to each other. A straight forward calculation is not possible but for purposes of discussion the four calculations will be treated separately.

2.1 Roll pass sequence

The various factors to be considered in the calculation of a roll pass sequence are pass geometry, roll bite, temperature and other rollability conditions, metal spread, technological limitations of reduction per pass and overall reduction, limitations arising out of mill parameters such as roll force limit and torque limit, and the requirements of mill productivity. In general the calculation of a roll pass sequence aims at maximizing the productivity of the mill without violating any of the constraints due to technology or equipment. Clearly the calculations relating to roll force, torque and power, along with temperature and productivity calculations are implicit in any scheme for computing the roll pass sequence. The resultant complexity makes this an ideal situation for the use of CAD. A few illustrative applications are discussed in detail.

2.1a Single stand cold mill: A cold reducing mill offers two major simplifications: temperature effects can be largely ignored and the metal spread is also negligible. Programs have been developed in which it is necessary only to define the various constraints of roll-bite angle, permissible reduction per pass and total roll force limit, mill speed, torque and power limit and available tension. The optimal reduction pattern that requires minimum number of passes is then automatically calculated. As a first step the rollability conditions are checked. The maximum draft which does not violate the constraints of bite angle and material reduction limits is then computed. With this value of draft the roll force calculation loop is referenced and the values of roll force and torque obtained are checked against the specified constraints. If any of the constraints is violated the draft is reduced and the calculation repeated. With properly defined gradients, a feasible solution is easily found.

2.1b Dimensioning of shaped passes: The need for accurate calculation of roll pass sequence is greater for shaped passes in that the roll grooves have to be cut according to these dimensions and any error in the grooves reflects on the quality of the finished product. The calculations are also more complex because the additional factors of metal spread and temperature assume an important role. As an illustration of the general

approach, the dimensioning of intermediate ovals with the entry and delivery squares defined will be considered. To start the iteration, some reasonable dimensions of the intermediate oval are assumed (table 1). With these assumed dimensions, the various constraints are checked. If any of the conditions is violated a gradient is computed. This gradient is used to calculate the next trial value. The iterative procedure is not prone to oscillation and normally converges within 4 to 6 trials.

2.2 Roll force models

The many roll force models available today may be grouped under one of two broad heads: models based on measured field data of specific energy consumption vs elongation and analytical models based on resistance to deformation vs temperature (for hot rolling) or yield strength vs reduction (for cold rolling). Used with care, both approaches give acceptable results.

The analytical models are, however, better in some ways. They can be used to calculate the roll force and torque only from the geometrical and physical data about the rolls and the rolled material. They are thus more general in nature and may be used more readily to examine the effect of extending the existing regimes of rolling practice.

Analytical models of the rolling process are of course extremely complex. The physical phenomenon is essentially one of inhomogenous compression of a material with variable yield stress moving within the roll bite with a frictional drag that varies in nature, magnitude and direction. The associated mathematics is further complicated by the geometry of a rectilinear work piece passing through a roll gap bounded by two curvilinear roll surfaces.

The many analytic models reported in the literature vary widely in terms of level of detail, complexity and accuracy.

The model that one adopts for simulation is dictated by the end use for which the simulation is developed. Three discrete levels of modelling can be identified. When the modelling is aimed at understanding and quantifying the physical phenomenon involved in rolling, a very high level of detail such as is offered by Orowan (1943) is required. At this level, physical assumptions are almost totally avoided and mathematical approximations are also not made. For purposes of day-to-day design, the simulations need to accurately reflect only the main features of the rolling process and they need to consider only the most important factors. Such models may include many physical assumptions valid for specific design regimes. Mathematical approximations may or may not be required depending on the mathematical complexity of individual design loops and the sensitivity of the whole model to the particular design variable.

Table 1. Iterations for dimensioning of an oval groove

Iteration no.	Oval width (mm)	Oval height (mm)	Norm of error vector
1	52.5	12.00	15.04
2	30.99	13.92	2.59
3	30.16	15.34	0.16
4	30.48	15.23	0.001

Input square: 21 mm. Delivery square: 16.2 mm

Lastly a model that is to be used for process control has to be sufficiently simple to ensure that the computation time adequately meets the control requirements. Such a model must of necessity include all reasonable physical approximations and many mathematical approximations as well.

As an illustration of the above, one may consider a problem that is of fundamental importance in the simulation of rolling process. In any rolling mill, material of large stock size A_1 enters at a low speed V_1 and is reduced to a smaller size A_2 leaving at a higher speed V_2 . The deformation is carried out by rolls rotating with a peripheral speed, V , $V_1 < V < V_2$. A basic question that is important for all calculations is the location of the neutral plane where the metal velocity is equal to the peripheral velocity of the rolls. For a precise determination of the neutral plane it is necessary to integrate the rolling equation:

$$df/d\phi = Ds \cos \phi (\tan \phi \pm \mu)$$

where f is the horizontal force per unit width, s the normal roll pressure, D the roll diameter, ϕ the angular coordinate of arc of contact and μ the coefficient of friction as shown in Figure 1 below, with full consideration of sticking/slipping friction, roll flattening etc. This requires numerical integration of a nonlinear variable parameter differential equation and the results allow for a precise understanding of metal behaviour in the roll bite.

For most design calculations, however, such complexity is not required and the use of a simplified closed form equation such as that given by Sims (1954) is generally acceptable:

$$\phi_n = \sqrt{\frac{h_2}{R'}} \tan \left[\left\{ \frac{\pi}{4} \ln(1-r) + (R'/h_2)^{\frac{1}{2}} \arctan \left(\frac{r}{1-r} \right)^{\frac{1}{2}} \right\} / 2(R'/h_2)^{\frac{1}{2}} \right].$$

Figure 1. Deformation in roll gap.

For purposes of on-line computer control even the above equation is not acceptable because of the computation time required, and a polynomial approximation of the type

$$\phi_n = a + bx + cx^2; x = \left(\frac{h_1}{R}\right)^{\frac{1}{2}} \left[\left(\frac{1-r}{r}\right)^{\frac{1}{2}} - \left(\frac{1-r}{\sqrt{r}}\right) \right]; r = 1 - h_2/h_1$$

which is sufficiently accurate may be used.

At the second level, which is of greater interest to design organizations, the calculation of roll force is generally straightforward; a notable exception being the estimation of roll flattening. As expressed by Hitchcock (1935), the extent of roll flattening depends both on the undeformed roll diameter and the roll force:

$$R' = f(r, P)$$

where R is the deformed roll radius, r , the undeformed radius and P , the roll separating force. Since the roll separating force is itself dependent on the contact arc, an iterative solution is called for.

Tension is an important technological parameter, particularly in cold rolling. For the results of simulation to be meaningful, the model used must take proper account of this factor. Further, in the process of optimizing the pass sequence, the iterative process must continually seek to maintain optimum levels of tension.

2.3 Temperature calculations

Temperature calculations constitute an essential part of all hot mill simulations. These calculations are required for estimating the force and power parameters of the process because they are mutually related to the temperature. Proper analysis of temperature conditions is also necessary for determining the thermal stresses in the rolls and for designing the roll cooling systems. Additionally, proper control of temperature is important from the viewpoint of the physical and mechanical properties of the metal and dimensional tolerance of the rolled product. Numerous temperature models have been reported in the literature. They are mostly quite detailed in concept but usually involve the "matching" of certain coefficients with experimental data which somewhat limits the predictive value of these models for design purposes.

For temperature calculations it is common practice to divide the roll into different zones as shown in figure 2. Within the roll gap, the heat transfer mechanism consists of heat generation in the strip through plastic deformation and conductive heat transfer between the rolls and the metal. Outside the contact area, both the strip and rolls lose heat through radiation, convection and to the cooling water.

The heat transfer mechanism in the roll gap is perhaps the most complex. In a model proposed by Bryant and Heslton (1982), the roll gap heat transfer to the rolls has been analyzed in terms of multiple line sources. Cernis' solution for line sources is used in conjunction with the method of superposition to calculate the steady state roll temperature distribution with depth at any angle. Similarly, a discrete model of the temperature distribution in the strip is also developed considering unsteady state heat transfer to the rolls. The two equations are solved simultaneously with the boundary condition being that the surface temperatures of roll and strip are equal along the contact arc. The heat transfer mechanism in other zones may be analyzed reasonably well with well-established finite difference methods.

Figure 2. Heat transfer zones of a work roll.

2.4 Productivity calculations

In order to obtain an accurate estimate of mill productivity, all mill simulation models incorporate realistic time studies. These time studies include gap time between pieces, material feeding time, acceleration time, run time at top speed, deceleration time, tail-out time and reversal time. Motor heating is always estimated as an integral part of the mill simulation and the motor characteristics of torque vs speed are fully taken into account. As an illustration of the extent to which detailed analysis is undertaken let us consider the acceleration of a tandem cold mill train. A program that is used for this analysis takes into consideration the variation in inertia of the input and delivery coils, the inertia of the drive trains, the rolling power in each stand and the torque vs speed characteristic of all individual motors. If one of the motors is in current limit at any point of time the acceleration rate is accordingly reduced. Similarly in the simulation of primary mills, the torque vs speed characteristic of the main drive motor is fully taken into account. If the motor goes into current limit after having accelerated beyond the base speed, the acceleration ramp is immediately reduced to a level consistent with the available torque and the combined inertia of the drive train and work piece.

3. Equipment design program

The mill simulations discussed above are required in order to properly size the rolling mills for specific requirements. For the detailed design of individual equipment they are of immense value as a starting point in that they serve to define the nature and magnitude of forces and stresses acting on the system. A different set of "equipment design" programs is required for the routine analysis and design of individual equipment such as mill housings, screwdown systems, drive systems, manipulators, roller tables, cooling beds and winding/unwinding reels. Both static and dynamic analysis are required. In addition, general purpose packages such as STRUDL II are also used as and when required for specific problems. Some of the more important programs in this category are discussed below.

In the ultimate analysis, the detailed design of individual equipment does influence the nature and magnitude of forces developed. Polukhin (1975) attempted to integrate these effects and obtained some rather interesting results but for most design purposes the prevalent method is to isolate the two. The results obtained are sufficiently accurate.

3.1 Analysis of mill stand stresses and deformation

The basic working element in the rolling mill is of course the mill stand which houses the rolls.

The roll separating force required to deform the metal acts on the rolls to cause stresses and deformations in the rolls, bearings, chocks, screws and the housing itself. As a result of elastic deformations in these elements, the effective (active) roll gap varies with the roll separating force.

Large variations in the active roll gap not only result in non-uniform dimensions of the rolled product and variations in interstand tension but they adversely affect the output of the mill and life of rolls. Roll force variations may be as high as 10–15 % of the nominal value and it is therefore important to increase the stand stiffness to as high a value as possible within the constraints of mill size. Proper understanding of mill stand stresses and deformations makes it possible to evaluate the effects of various factors on the stiffness of the stand and optimize the design of the mill housing. The models used for these studies are based on frame analysis and they fully take into account the deflections of the rolls, bearings, chocks, screws and also the compression of the working fluid in case of hydraulic mills.

Dynamic analysis of the mill housing is also required for the design and optimization of automatic gauge control systems as described later. For these purposes it is generally sufficient to use a second order model for the mill housing.

3.2 Torque amplification studies

In much the same way that the mill stand serves to exert the forces required for deforming the metal, the mill spindles must be properly designed to transmit the torque from the motor to the rolls. The sharp increase in operating speeds of mills during the 1960s led to several premature failures of the mill drive components which could not be explained by the conventional steady state analysis used in mill design upto that time. This drew attention to the phenomenon of transient torsional vibrations in mill drive systems. Transient oscillations can produce mechanical torques many times greater than the electrical ratings and resonant or near resonant conditions can lead to fatigue failures. Because of the large number of masses and gears in their drive trains the hot strip mills are particularly susceptible to high torque amplifications, and the first attempt at such analysis was with respect to these mills. In most cases these drives are subjected to linearly varying torques only and the drive systems may be modelled as a linear oscillatory system with proper representation of the inertias, torsional stiffness, damping action in the bearings and the applied torques. In the primary (reversing) mills such as the blooming and slabbing mills, nonlinear effects such as backlash become important and linear models no longer suffice.

In either case, for adequately describing the physical system, the mathematical model has to be of high order. The overall drive system consists of two subsystems i.e. the electrical drive and control system and the mechanical system. In earlier studies relating to hot strip mills the mechanical system only was analyzed but for the reversing primary mills, the interactions of the two subsystems become important and a more elaborate model as shown in figure 3, is required.

The solution of the associated differential equations has become possible only after the development of computer programs. In addition to solving the natural frequencies and normal modes, these programs also determine the transient response to several

Figure 3. Mathematical models used for dynamic analysis and synthesis. (a) Block diagram of drive system and (b) Lumped parameter model for torque amplification studies.

types of inputs to represent as far as possible all types of disturbances such as ramming of bar, slipping in the roll bite, nonuniform section, nonuniform reduction etc.

Computer studies of the large hot strip mills have occasionally led to changes in the proposed design to limit torque amplification to acceptable values. For the reversing mills the computer studies are reported to have led to substantial improvements in the optimization of the speed regulation compensator.

3.3 AGC system response studies

The influence of mill stand rigidity on the dimensional tolerances of the rolled product has been referred to earlier. In order to meet increasingly more stringent demands on dimensional tolerance automatic gauge control (AGC) systems have been developed to compensate for these variations. For proper control these systems are required to have a response time of about 20–30 m sec and a frequency response that is flat upto about 10–15 Hz. Except in case of smaller rolling mills these systems are generally controlled by a microprocessor or a computer.

The design and optimization of AGC systems is generally based on detailed computer models that include all parts of the system i.e. the physical plant, the sensors, the controllers and the actuators. For purposes of illustration, a computer model of a single stand hydraulic AGC system will be considered. A schematic of the same is shown in figure 4. The transfer function of each component is carefully determined and the computer simulation is used both for time domain analysis and frequency domain analysis. Such a model makes it possible to analyze the response to a step or other disturbance in incoming strip thickness, material hardness, roll separating force, tension, speed, etc either with or without AGC. For design optimization the general form of the compensator transfer function may be preselected and the different coefficients varied within a specified range. Clearly the validity of these simulations depends on the

Figure 4. Block diagram of AGC system model.

accurate modelling of individual components such as mill stand, cylinder, load cell and servo valve, and also on the use of an accurate roll force model.

4. Graphics applications

The mathematical models and simulations described so far have played an important role in transforming rolling mills design from the domain of empiricism to an analytical level. Since the engineer works in graphic as well as mathematical terms, the results of analysis needed to be translated into graphic form. Besides the tedium of such work, the likelihood of error and the noncreative expenditure of time required, served as major disincentives for the widespread use of these techniques. New developments in "computer graphics" have finally allowed the design engineers to overcome these problems and communicate with the computer in a truly natural form.

The term computer graphics is very broad and includes numerous peripheral devices such as xy plotters, printers and drafting machines and graphic display screens. The most rudimentary application of computer graphics is for plotting the computed results as graphs, bar charts, etc. Examples of such applications include the plotting of transient response of drive systems, plotting the locus of linkages, plotting the profile of gear teeth, etc.

4.1 Roll groove drawings

At a somewhat more advanced level, computer graphics may be used for generating schematics and mechanical drawings of predefined shape. The graphic display screen is not essential for these applications but it may be used if available.

A popular application at this level is the generation of roll groove drawings. The geometry of these drawings is more or less fixed and all the dimensions may be obtained from the programs that calculate the pass dimensions as discussed earlier. The program developed in the present author's establishment (MECON) consists of the following parts:

- (i) selection of a standard scale factor,
- (ii) calculation of all coordinates for the main drawing and for all dimension lines,
- (iii) selecting a position for the drawing on the plotter and drawing of boundary lines and name plate,
- (iv) plotting the groove drawing,
- (v) plotting the dimension lines and inserting the dimensions and
- (vi) plotting of all textual information.

The data used for generating the groove drawings can also be used for generating roll drawings. This feature has been implemented by some mill builders and is under development at MECON.

4.2 Hydraulic schematic circuits

One of the earliest applications requiring the use of an interactive graphics terminal is the generation of schematics made up of items in a predefined menu. An example of such application is the interactive graphics software presently under development at MECON for hydraulic schematic circuits required in rolling mills design. User-defined keys have been associated with all standard element symbols such as tank, pump, filter, accumulator, check valve, servo valve etc. Working on an interactive graphics terminal, the designer can develop a complete schematic consisting of any arbitrary combination of these elements.

The elements can be individually rotated and scaled with conversational commands. Moreover the drawing as a whole can also be scaled for viewing on the screen or drawing on the plotter. Care has been taken to facilitate editing functions such as deletion and insertion of individual elements or complete circuit branches.

5. Summary and conclusions

The large number of simulations and design programs being used for rolling mills design have been developed over a period of several years. The mathematical models have been steadily upgraded to include the greatest level of detail possible within the limitations of computer time. Most design organizations have constantly updated the material characteristics to conform to field measurements. The software has generally undergone numerous modifications in order to meet the specific requirements of designers without sacrificing generality. There has also been a persistent effort to make the programs fully automatic as far as possible.

With the availability of interactive graphics facility, the present area of thrust is towards increased use of computer graphics. Wherever possible the calculation programs have been integrated with graphics software as described for the design of roll grooves. Such integration serves to eliminate the tedium of mechanically translating a computer printout into a drawing and allows the rolling mills design engineers to iterate more design concepts and trade-offs in a given time and greatly increase his creativity and productivity.

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