Development of Model-intensive Web-based Rolling Mill Applications

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ABSTRACT

Model-intensive web-based steel rolling mill applications have been developed in metalpass.com. They include pass design suites AutoForm and FreeForm, mill force/torque prediction suite, temperature profile program with finite-differential method for rolling and water/air cooling, and microstructure prediction application, etc. Coupled with tension models, the FreeForm is particularly useful for high-speed rolling blocks, and for both designing new passes and examining existing ones. Multiple algorithms are applied to ensure both speed and accuracy. Issues in developing each of the applications, such as process modeling, data modeling, model verification, object-oriented programming, and data management, etc., are discussed.

1 INTRODUCTION

Some background information could be helpful for readers to understand how the development of model-intensive rolling mill applications became author's career focus. After earning B.S., M.S. and Ph.D. (Germany, 1995) all on steel rolling, and especially after completing the entire set of rolling process models during the work for a top U.S. mill supplier, the author gained certain understanding on the complexity of steel rolling process. The developed models were per request of the mill supplier to target several critical mill design/operation weaknesses. Though the models had high prediction quality, they were quite complicated and beyond understanding of average engineers. Some U.S. engineers, due to limited rolling-process background training, may prefer simpler solution. The author also knew that many complicated interactive factors could only be handled in high-quality software. For those reasons, the author started to work as mill software engineer (on Level 2, etc.). Ten years later, with 30 computer evening-classes completed, sufficient programming skills accumulated and the models further refined, the author now focuses on developing his own model-based mill software. Due to the good future of web-based application, the author pays special attention to running software in the web.

2 ROLLING PROCESS MODELING FOR WEB-BASED APPLICATION

2.1 Significance of Rolling Process Modeling

Traditionally, a steel rolling mill was operated mainly based on the experience. Roll pass design was, by many people including some theory-oriented academics, considered as a combination of experience and art. Even some expert mill-designers with life long experience, still claimed that many mill-operations are easy to know but hard to explain. It is a common view by many people, that every mill has some practices against the common sense. However, people have above-mentioned view may because they do not have sufficient understanding of the mill process. Steel rolling operation is a highly complicated process. It involves not only the mechanical principle but also the metallurgical requirements, and more (e.g. automation). Its mechanical and metallurgical aspects are outlined in the following paragraphs.

Mechanical aspect. With a reduction in height during rolling, metal moves towards directions of width (spread) and length (elongation, forward slip and backward slip). The metal flow and force/power requirements depend on height reduction, roll diameter, shape of deformation zone, speed, temperature, steel grade, interstand tension, etc. Due to forward slip, stock exit-speed is higher than roll circumference speed. In grooved rolling, effective roll diameter should be used instead of collar diameter. Since long, the rolling speed for the wire rod rolling has reached over 100m/s, and continuous rolling demands accurate prediction of the rolling speed and interstand tension. The interstand tension, especially in a high-speed rolling block (multiple stands driven by a single motor), may greatly change the spread and forward slip and cause problem in maintaining volume constant. Failure to maintain sufficient tension would cause flutter (mill vibration) which would lead to high noise and leave the equipment not operable. The heat generation during the high-speed rolling (speed over 100m/s, with strain rate over 3000/s) is significant and greatly affects force and power prediction. In addition, measuring and thus modeling flow stress for high strain rate (over 500/s, or even over 100/s) is always an issue for the industry.

Metallurgical aspect. Both softening and hardening phenomena exist in the rolling process. During rolling, there exists dynamic recrystallization in the stock. In the interpass time, static and metadymical recrystallization and maybe also grain growth occur. In order to achieve good mechanical property of a rolled product, grain growth and phase transformation should be controlled. What makes the processes more complex are the addition of micro-alloys and the practice of interpass hold (e.g. for some high-quality grades) of the work piece. Between or after rolling passes there is usually controlled water cooling to maintain certain temperature profile favorable to microstructure evolution and thus high mechanical properties. Missing the targeted temperature would reduce the rolled steel properties. Desired microstructure needs to be achieved by both controlled rolling and controlled cooling.

Interaction. It often happens that recrystallization is only partially completed in modern rolling process (normally in lower temperature than earlier). In this case, a given pass may inherit a part of the strain from former passes. For example, when a pass strain is 0.3, the effective strain, which should be used for force and torque calculation, could be 0.5 or even more. Besides, initial grain size has effect on flow stress. On the other hand, strain and strain rate affect microstructure change; possible non-homogeneity in local deformation may result in different local temperatures and thus different local microstructures. In general, the interaction during low temperature rolling plays more important role than in high temperature processing. Hold of steel (e.g. plate) between passes may lead to a force error of -10% to 50% [1]. One of the worst cases could be when the pass schedule is generated by a level 2 model (usually in flat rolling) and the rolling is performed in the two-phase region due to model prediction error for temperature. In this case, the flow-stress model failure would cause very high force error (e.g. 40%) and the Level 2 model would generate a very unreasonable draft schedule that would lead to quite poor shape of rolled strip/plate [2].

Process models and software. Many interactive influences of various parameters need to be mathematically described to improve the mill design and mill operation. Rolling process models describing those interactive relationship are often far beyond the understanding of average design or operation engineers. Those interactive relationship may only be handled with software, while in current design; they have to be greatly simplified. The emerging of new types of mills and new rolling technologies, however, leaves traditional models or empirical data not accurate enough to describe the rolling process. Today's technological development has made it possible to take into account major factors of rolling process, and advance in computer technology has made it affordable to acquire more detailed information of the process. In this situation, a software developer with good understanding of the interactive processes and solid programming knowledge is essential to bridge the gap and to bring many new concepts into real-world application. As long as the software is completed, it would greatly improve both mill design and mill operation. The demand of high-quality mill knowhow and availability of the author's models leads to the development of model-based rolling mill applications. With the accurate models, the developed software would be highly intelligent.

2.2 Future-Potential of Web-based Mill Application

Increasing globalization has significantly changed the face of the steel industry. Major US steel producers such as AcelorMittal and Gerdau Ameristeel operate in multiple continents or multiple countries. Even Nucor is located in many states of USA. Teamwork from various countries or regions plays more and more critical role. The development team for Nucor Castrip, for example, locates in multiple flat operation facilities in Indiana, Carolinas and Arkansas, etc. Web-based engineering application is the right way to meet the design and development needs for the global operation. Members of development team from all over the world may use the same system and coordinate data input/output seamlessly just as if they were sitting in the same room. Businesses like IBM have since 10 years encouraged employees to work from home through web-based applications.

Internet probably represents the most significant technical progress in the past 20 years. Internet access today may be as convenient as listing to radio. Mission critical applications, even those for financial management, are almost fully web-compatible. The engineering design and development using internet, though still relatively less popular, are quickly catching up. Most design and development assignments may be performed via web-based engineering applications, if those applications are available through internet.

A web-based rolling mill application is very convenient to use. It can be accessed:

- anywhere: in office, at home, during travel, so team members from all over the world can easily work together;
- any time: since a website is usually always available;
- by any one: a joint user account for a team allows anyone to work on the project;
- with low maintenance cost: with minimal installations, etc.
- with short learning period: since almost all users have experience in internet.

Even from development cost, the web-based application is now still in advantage. Since the release of the Microsoft.Net, development of web-based applications has become easy and can be done in the same way as Windows-based application. Some features in web environment can even be easier to implement than in Windows. In Windows application, data communication, memory management and multiple-user features, for example, are usually implemented with programmer's coding and this takes tremendous amount of work. In the web environment, however, they can be mainly handled by the web server, which is available for free. On the other hand, an internet application, with large number of users all over the world, can easily be licensed at a lower price than Windows one.

For above-mentioned reasons, the author paid special attention for developing web-based mill application, especially for design and development software. Even for online system (Mill Level 1, Level 2 and Level 3, etc.), web-based ones still have advantages. Though Windows- and OpenVMS-based Level 2 systems currently dominate the market, more and more mills would accept web interface. System implementation of the Level 2 system would not have many differences between web-based and Windows-based versions with respect to the data collection, data communication and mill process modeling. Web server is installed by default for any server version of Windows. However, for web-based systems, quite a portion of memory management would be handled by the web server instead of the programmer. At present, advantage of the web-based design and development software (for roll pass design, force/power calculation, temperature and microstructure prediction, etc.) would be more easily accepted than online automation systems.

3 WEB-BASED ROLLING MILL APPLICATIONS

Examples for the web-based rolling mill applications available in metalpass.com are roll pass design suites (AutoForm series [3] and FreeForm series [4]), mill force/torque prediction suite [5], temperature process/profile program [6] with finite-differential method for rolling and water/air cooling, and microstructure prediction application [7], etc. There are also several data modeling applications such as for Flow Stress [8], High-Temperature Properties [9], and General Properties, etc., which will be discussed in the application development section.

3.1 Common Features for the Mill Applications

All the programs have two unit systems available: English and Metric. For roll pass suites, user can select to perform the design with either hot dimension or cold dimension. If the cold dimension is selected, the related program applies a material specific thermal expansion factor to transform it to hot dimension. The author has a rich collection of material-specific coefficients in this aspect [9].

For the roll pass design programs, material effect on the deformation (spread, etc.), for grades listed in the Table 1, is considered. For the force, torque and power calculation, the stock materials listed in the Table 1 are used as base grades. Further grades can be calculated by applying a load factor (the ratio of a given grade strength to the strength of the base grade).

For all the roll pass design programs, the system offers an option to suggest design data such as roll gap, roll diameter, corner radius, fill ratio, aspect ratio, which are often difficult to determine for inexperienced designers. For high accuracy, the system predicts rolled shape including the free radius (the radius of the free side in the roll gap). Further examples of selected factors considered in the roll pass design programs are listed in the Table 1.

Table 1: Selected influence factors on spread and forward slip, etc.

Geometry	o Roll gap geometry and stock reduction with various prediction procedures such as Shinokura-Li, Hensel-Li, etc. o Empirical factors such as Shinokura coefficient determined from large number of tests and mill field data
Stock material	o AISI 1015 Carbon o AISI 1025 Carbon o AISI 1035 Carbon o AISI 1045 Carbon o AISI 1055 Carbon o AISI 1065 Carbon o AISI 1070 Carbon o AISI 9255 Spring o AISI 302 Stainless o AISI 321 Stainless o AISI 430Ti Stainless o AISI 446 Stainless o AISI 52100 Bearing o Cu99.97 o Al99.5
Roll Material and Cooling	o Cast Iron and rough steel rolls, Dry o Cast Iron and rough steel rolls, Water cooled o Cast and smooth steel rolls, water cooled o Hard cast rolls, emulsion cooled o Hard metal ground rolls, water cooled o Hard metal ground rolls, emulsion cooled
Rolling Process Parameter	o Speed (calculated from final speed and mill type) o Temperature o Interstand tension (mainly for FreeForm) o Friction (predicted based on other parameters)

3.2 Roll Pass Design - AutoForm Series

The aim of developing the AutoForm series [3] is, based on minimal user input and by applying comprehensive mill models, to deliver maximal output with highest possible output. With its full-automatic and easy-to-use features, user only needs to enter basic operation parameters to the table-like input form, and the system will run the loop for trial-and-error design. Even for the basic input parameters such as the gap (parting) and fill ratio, the system still provides option to suggest values. A suggested value will be used if user checks the corresponding “Let system determine” box. In fact, the least parameters the system needs are the initial shape and final shape. The roll diameter, etc. can be suggested based on the commonly used values in the rolling process, if user prefers. This series assumes that user does not have any experience or knowledge for roll pass design.

Inside the system, however, there are very sophisticated models to cover every detail of the roll pass parameters. Besides the geometry, a long list of rolling process parameters such as those described in the Table 1, that most roll designers often ignore, are used to improve prediction accuracy. Those parameters, such as stock material, temperature, and final speed, etc., is not hard for mill engineers to obtain. However, it is difficult for roll pass designers to determine their influences on spread and forward, etc. The roll pass program does this part of the work.

By default, the programs provide user with the option to enter rolled shapes. For example, the rolled round is formed by four circles with each diameter larger than the round diameter. This is a very common shape during rolling from pass to pass. If the entry shape is a perfect round (or square), user may check the box “Perfect round” (or “Perfect square”), and enter only the round diameter (or square side).

Currently the AutoForm series has five programs available, as follows:

1) Round-Oval-Round (2 passes)
2) Square-Diamond-Square (2 passes)
3) Billet-Box-Square-Oval-Round (4-passes)
4) Billet-Box-Oval-Round (3-passes)

5) Box-Box (2 passes)

New pass sequences would be continuously added to the series. For example, the Box-Box sequence is a recent addition based on a recent consulting project. The Box-Box pass sequence can be used for passes from breakdown, blooming, roughing throughout finishing stages.

Sequence 4) is a variation for the sequence 3). This sequence is used if the entry shape is rectangle but not a square. Consequently, the total number of passes for the entire mill would be odd.

The Billet-Box-Square-Oval-Round sequence is initially for the first four passes of the rod train (e.g. that of Morgan type mills). Recent extension added many new features. There are various design options, for example, for meeting biting requirement:

a) Fixed sizes and changeable roll diameter
b) Fixed roll diameter, changeable sizes
c) Fixed all, for pass verification

The biting condition is usually checked with the discard diameter. If the condition is not satisfied, the system may automatically find right solution by changing either roll diameter or pass reduction. If user wants to manually design the passes to achieve certain size, by selecting c), the system would simply calculate all parameters and leaves the decision to the user.

3.3 Roll Pass Design - FreeForm Series

This series [4], currently including Oval-Round and Diamond-Square, is particularly designed for experienced roll pass designers. It provides full freedom of trial-and-error design for the pass and groove parameters. For every trial, the system calculates spread, forward slip, roll RPM, and all other critical parameters. A large number of passes, from roughing, intermediate, pre-finishing to finishing (wire block) passes, can be completed in a single project. User has freedom to specify design procedures for spread and forward slip for every pass. Either system determined spread factors calculated from the process models or spread value from user are accepted. The program can perform system learning if the measured widths are available from user.

Though this set of programs apply for all roll pass designs, several cases of applications are in special advantage: one is for high speed wire block (No-Twist Mill, etc.) which is particularly challenging for roll pass designers; another is to study existing pass schedules for improvement or to modify existing pass schedules to create new ones. In addition, programs in this series are also capable of predicting stock cross-sectional differences among header-end, tail-end and the rest part of the stock.

A special feature for this set of programs is that it employs an accurate procedure to account for effect of tension/compression on metal flow (spread, forward slip, etc.). Tension effect is critical for studying existing roll pass. During a test by applying the tension effect, a program in this series successfully replayed the real-world rolling (mal)practice based on field measurement data for roughing, intermediate, pre-finishing mills, and wire block. For example, mill setup data (geometry, gap, speed, grade, temperature, Roll RPM, etc.) used by mill operators were entered into the program. The predicted width, speed, etc. for each pass fit excellently with the measured ones. Both the program prediction and the field measurement indicated that some passes had very small spread, while in the neighbored passes there were much higher spread values. This problem is due to the inter-stand tension/compression caused by pass design error (rolled areas, forward slips, etc.) in the existing pass practice. Therefore, the FreeForm roll pass program is the right tool to evaluate the existing pass schedules and to suggest remedial measures to fix the problems.

Extensive software verification has been conducted. For example, the Oval-Round program has been tested with 14 sizes and about 60 passes in the wire rod rolling blocks, based on on-site measurement for stock geometries and speeds. In the wire block tension is usually unavoidable, and the feature of the tension correction for spread and forward slip, etc. significantly improve prediction quality.

Due to the large number of passes and thus large amount of data involved, programs in this series allow user to save all the input and calculated data into a file. The saved files can be read back into the program later.

3.4 Mill Force/Torque Prediction Suite

This is a set of programs [5] designed to calculate roll separating force, rolling torque, and power, etc. Pass sequences include: Round-Oval, Oval-Round, Round-Oval-Round, Square-Oval, Box-Box, Square-Diamond, Diamond-Square, Square-Diamond-Square, and General Pass. Material grades available as base grades are listed in Table 1. Data for other grades can be obtained by applying a load factor. Very simple input data are required, primarily in sizes and operational parameters (temperature, speed, etc.). However, for the logics and calculation, every detail involved is carefully determined:

- Projective contact area. Elementary slab method was used by constructing imaginary contour, together with modifications from spread, pass sequence and fill ratio, etc. For some passes, contact area models were used based on the studies on the shapes of contact areas in various pass sequence.
- Mean flow stress. Flow stress model is specifically developed for a wide strain rate range 0.05-500/s (applicable up to 3000/s).
- Shape factor (Q-factor) and lever are ratio. The Shape factor model used in the programs considered pass sequence, entry billet shape, contact, etc. The lever arm ratio was experimentally established for each pass sequence.

3.5 FDM Temperature Profile - Rolling and Controlled Cooling

This application [6] uses finite-differential method (FDM) to determine temperature profile from billet, over the rolling and cooling, etc. to the final production stage. The temperatures in the rod core, in the rod surface, and at the rod middle point between the rod core and the rod surface, etc., can be determined and plotted over either the time or the distance from the start of the rolling. A large number of the stages can be included in a project with the possible stage type:

- Rolling: with calculated heat generation and heat transfer coefficients
- Interpass cooling: with estimated heat transfer coefficient
- Controlled cooling (water boxes): with predicated heat transfer coefficients based on water-box cooling parameters

Complete models on the heat transfer coefficients during water-box cooling, developed based on near ten field tests and lab experiments, were used. The heat transfer coefficients were modeled as function of water flow volume, speed and pressure, and the temperature of the material, and so on. Heat transfer coefficients during rolling and interpass cooling were also well modeled considering temperature of the stock and rolls, speed and roll pressure, etc.

For heat transfer coefficient in each stage, option for direct user-input instead of model prediction is available.

3.6 Microstructure and Property Prediction Application

This application [7], equipped with various microstructural models, allows average engineering personnel to simulate very complicated microstructural processes, by simply filling in rolling/cooling process parameters. The microstructure models the author developed cover over 10 materials. In the online demo, the following material/Process are available:

- D73 (0.75C, 0.54Mn), Rod rolling
- 24MnV4 (1.08Mn, 0.12V), Rod rolling
- C-Mn (0.06C, 0.7Mn), Strip rolling

For every material there are about 30 coefficients (slightly different from material to material) which describes material properties, progress of the static/meta-dynamic/dynamic recrystallizations and grain growth, etc. As long as user selects a material, those coefficients are directly read into the calculation program. Major input data from user are such as:

- strain and strain rate for rolling, which can be calculated from input heights and either speed or time, etc.
- temperature
- time for rolling and/or cooling
- heat transfer coefficients for controlled cooling, with option available to calculate the coefficients from water volume flow, water pressure, water temperature, etc.
- initial grain size, which can be suggested by system. It would not have much influence for the grain after several passes, so certain error will not cause much trouble to the final result.

Output parameters are such as fraction of the recrystallization, recrystallized grain size and effective strain (pass strain plus retained strain), etc.

3.7 Other Applications

Pass Manager [13]. It is a program available to study number of passes needed to roll a size, or the size range that can be rolled in certain number of passes. This program can examine whether a mill is operated in an efficient manner and whether it is feasible to roll new sizes or new grades. In the current version, entry stock can be either a square/round billet, or a rolled shape of round or square. Finish shape is either round or square. More shapes would be added. Available cases cover any number of passes in any one or more of the roughing train, intermediate train, prefinishing train and finishing rolling block (NTM). The program provides learning features for the user to apply a modification factors. Examples of the mill differences are operation speed, roll dimension and lubrication condition, etc.

Applications under development or testing. Example of those applications are:

- Slab Management and slab optimization. It is to manage slab inventory for easy and effective slab-providing, and to optimize the slab size and slab grade, etc, through rolling pass simulation and prediction of rolled steel properties.
- Mill Diagnosis System. It is designed to diagnose the weakness of the Level 2 model. If a weakness is identified, such as too many passes or too high prediction error, the system would further identify the cause of the weakness.

4 DEVELOPMENT OF THE MILL APPLICATIONS

Selected development activities related to the mill applications will be discussed in this section. They include development and application of the rolling process models, model verification, software testing and web-related handling. Multiple algorithms are applied in the software development to ensure both speed and accuracy.

4.1 Mill Process Modeling and Data Modeling

Dozens of rolling process models were applied in the roll pass design programs. Selected models are as follows.

- Spread model, with one or more models used. The system may integrate multiple models for automatic, quick design; it may also use a certain procedure based on user selection
- Spread coefficient model, such as models to predict Shinokura factor
- Forward slip models, including those for neutral angle prediction
- Free radius model, to predict the radius of the free side (usually in the gap region without contacting any roll)
- Maximum bite angle model, for maximum of the allowed bite angles based on friction prediction
- Friction model, to accurately predict friction coefficient based on about 10 influence factors

Spread

Various spread formulas were developed based on large amount of measurement data, to satisfy various rolling conditions and design options. Some if them are the extensions for the existing procedures. For example, Shinokura procedure [10] is considered an effective way to account for geometry, but it does not have coverage for other critical factors. Further process modeling was performed to include rolling process parameters (speed, temperature and tension, etc.), steel grade, roll material and cooling/lubrication condition, and so on.

Other spread prediction formulas, such as Hensel, Wusatowski, etc., were also evaluated, improved and applied in the mill software, as procedure option for user selection.

Forward Slip

Wusatowski forward slip procedure is one of the most popular methods used in the industry. However, the most flexible aspect, the prediction of the neutral angle, etc., is difficult to determine. Further modeling for neutral angle in various pass sequences was performed.

Force/Torque/Power during Rolling

The modeling in this section is further divided into three sub-sections, for the modeling of

- Flow stress and mean flow stress
- Shape factor for force and lever arm ratio for torque
- Projective contact area

Flow stress is the function of strain, strain rate, temperature, material and initial grain size. Flow stress models for the frequently rolled steels were established. Some examples are shown online [8], which collected about 2000 flow stress data models. Shape factor and lever arm ratio account for the effects of the roll gap geometry and friction. Though the Projective contact area is very easy to model for flat rolling, it is very complicated for the shape rolling such as those for oval, round, square, diamond, angle, rail, U-section and I-beam, etc.

Property Data

Accurate prediction of the rolling process parameters also requires high-quality data model besides process model. Data modeling includes mainly those for material data, process data and boundary data. Most material data for the hot rolling are temperature dependent. Examples for those material data are:

- Specific heat in function of temperature
- E-modulus in various temperatures
- Thermal conductivity, temperature conductivity, density, etc.

Boundary Data

Boundary data refer to those describing contact features of the rolling stock with others, typically rolls, cooling water or air. Examples for the models are:

- heat transfer coefficient during rolling, depending on scale formation, roll cooling, pressure, roll RPM, etc.
- heat transfer coefficient during controlled water cooling, in function of water flow (GPM), flow speed (FPM), water temperature and water pressure, etc.
- heat transfer coefficient during controlled air cooling, in function of air flow (GPM), flow speed (FPM), air temperature and air pressure, etc.
- Friction coefficient during various rolling conditions, in dependence on scale formation, stock and roll material, rolling speed, rolling temperature, roll pressure and gap geometry, etc.

Heat transfer coefficient models are critical for high-quality temperature prediction. Friction model is the basis for accurate prediction of the maximum bite angle; it is one of the major factors for the force prediction as well. For hot rolling, an unique friction model was created taking into account groove sequence, steel grade, roll material and lubrication, rolling speed, rolling temperature, etc.

Data Sources and Development Stages

The influence factors of steel grade, temperature, roll cooling/lubrication and roll material, etc. were developed based on measurements performed in several laboratory mills, such as the one showed in the Table 2 below. It is a four-stand continuous mill with controlled rolling and cooling. The rolling speed is up to 70m/s. Most process parameters are fully measurable and adjustable. For the mill operation, it is quite similar to a production mill. Data for the model development and model verification were from various research reports together with over 40 Ph.D. theses based on the testing results in this mill.

Table 2: High-speed testing mill [11]

Roll Diameter	1 x 150-170mm (5 $^{15}/_{16}$ - 6 $^{11}/_{16}$ in) 3 x 190-215mm (7 ½ - 8 ½ in)
Roll length	80mm (3 $^{1}/_{16}$ in) (roll slice)
Max. Roll separating force	90KN (150mm/6". dia.), 115KN (190mm/8" dia.)
Max. Torque	8.5KNm (150mm/6" dia.), 15KNm (190mm/8" dia.)
Driving Power	160KW (per stand)
Rolling speed	70m/s (14,000 FPM)
Entry size	12-20mm dia. (1/2-3/4 in.), 1-10m length
Finish size	> 5.0mm (0.20in.), and analog square, flat, etc.
Stand arrangement	H-V, H-H-H-V and H-H-V-H
Cooling	Water cooling pipe; Air cooling zone

Another set of the mill data for the model development was from a five-year lab mill test in USA. Large number of pieces were rolled and the data well recorded. However, due to some testing design issues, some key factors were missing and thus some influence factors could not be isolated. Even though, it was sufficient for verification of the models. Further data sources for the model development were the publications in various countries, primarily in the four languages (English, German, Chinese and Japanese) which the author uses.

Intensive model development started in 1990 as the author was working for Ph.D. on the steel hot rolling process modeling [12]. Further model development was conducted in USA to assemble and systemize models for predicting metal flow (spread, forward slip, etc.), force/torque/power, and microstructure and steel property.

4.2 Model Verification

Extensive rolling tests were performed to acquire geometry and process data for model verification. In the following Fig. 1 and Fig. 2, the calculated spread $\Delta B/B_0$ with the modified Shinokura, or called Shinukura-Li, is compared with the measured spread value. An excellent match has been received. In Fig. 1, certain errors occur when $\Delta B/B_0>0.32$; however, $\Delta B/B_0$ in the real production line is usually far below 0.32.

For the RD-OV case (Fig. 1), the error for $\Delta B/B_0$ is about 1%-5%, which translates into a width error of only 0.25%-1.25% (with example of an initial width of 40 mm and $\Delta B/B_0$ value of 0.2). In the OV-RD case (Fig. 2), the error of $\Delta B/B_0$ is about 3%-10% . This is equivalent to a width error of about 0.75% to 2.50% (for an initial width 40 mm and a $\Delta B/B_0$ value of 0.2).

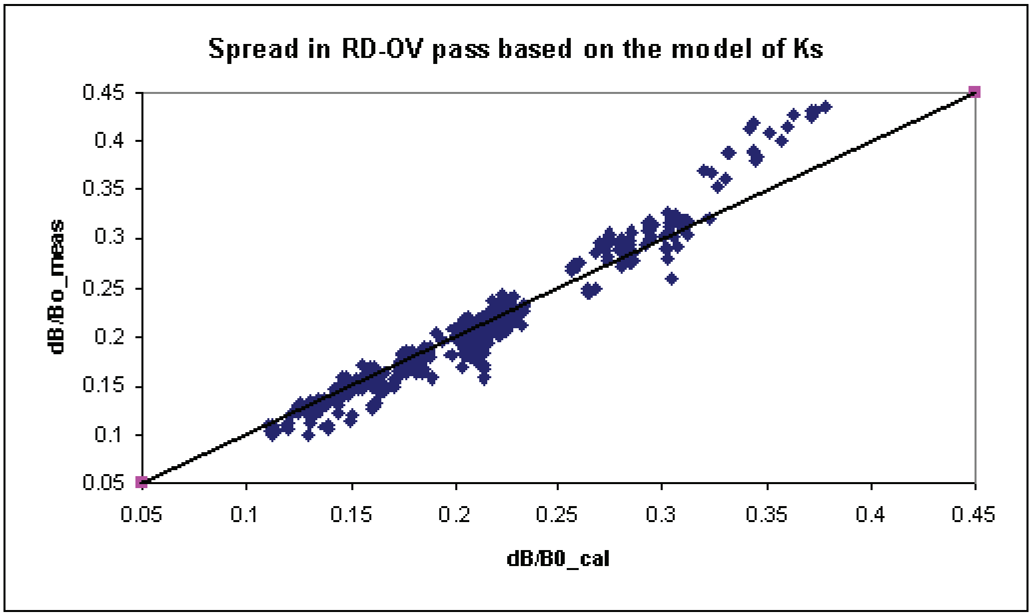

Fig. 1: Calculated $\Delta B/B_0$ values for RD-OV with modified Shinokura, in comparison with the measured ones

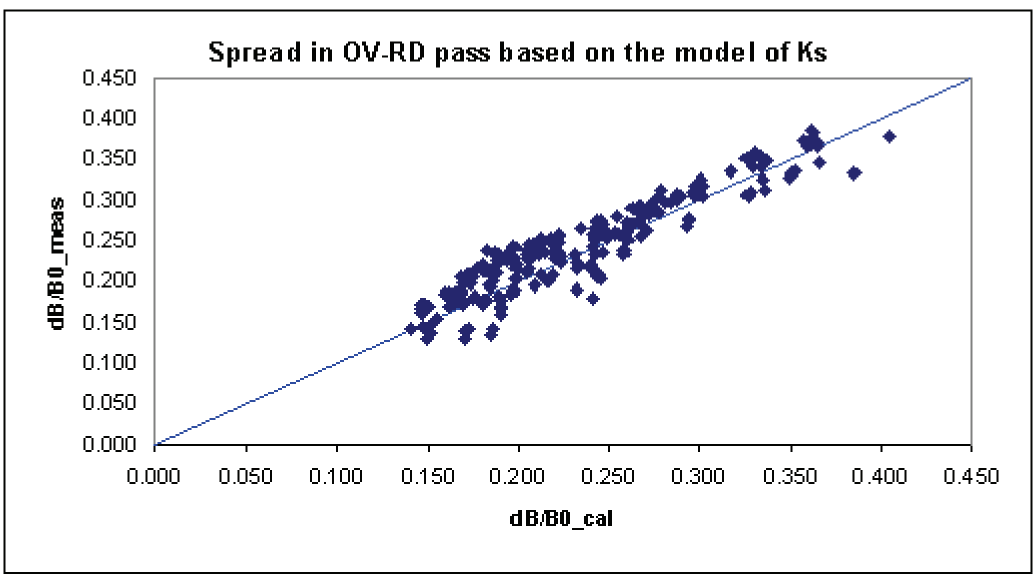

Fig. 2: Calculated $\Delta B/B_0$ values for OV-RD with modified Shinokura, in comparison with the measured ones

The spread model (Shinokura-Li) was further developed and verified based on mill tests in modern high-speed wire block. As an example, measurement was conducted in a production mill, during which holes were cut on a wire block cover, so that rolled stock geometry could be measured during the rolling production. Measurement was done for about 14 sizes, 60 passes, with 2-8 passes per size. Rolling speed was 15-60 m/s (3000-12000 FPM). A comparison of some measured and predicted Shinokura factors (Ks) was done and it showed excellent consistency. During the evaluation, tension effect on the Shinokura factor was taken into account.

Fig. 3 below shows a good correlation between the measured forward slip and that calculated from modified Wusatowski procedure (or may be called Wusatowski-Li).

In the Fig. 4 below, the calculated forward slips for the finish passes of various sizes are compared with the measured ones. The measured values were from a high-speed wire rod block (No-Twist Mill) of a steel plant.

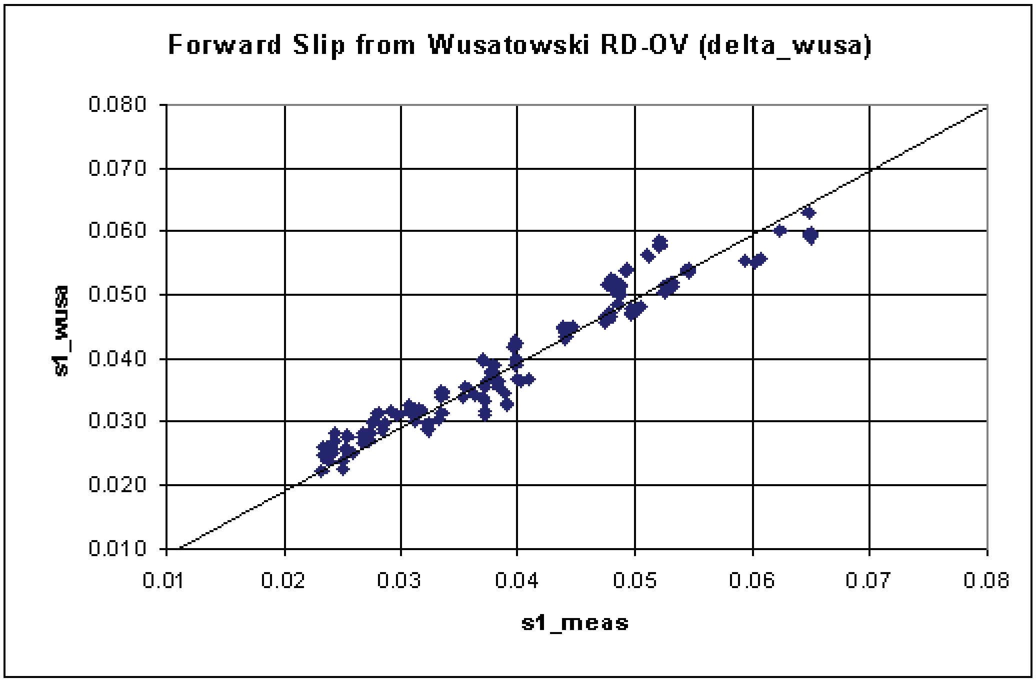

Fig. 3: Predicted forward slips and measured values in the lab mill data (based on Wusatowski and a new model for neutral angle)

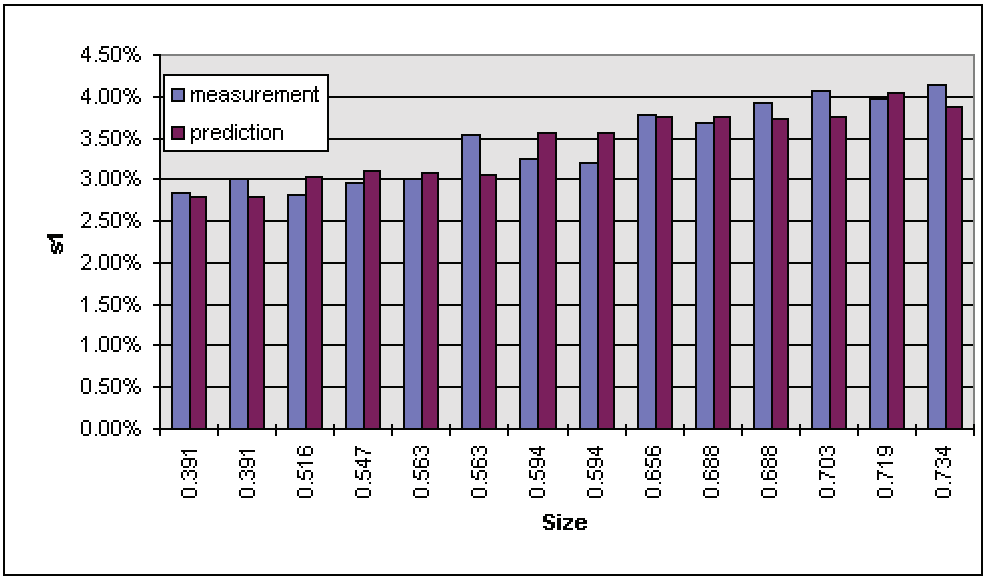

Fig. 4: Predicted forward slips and measured ones in the finish passes of a production rolling block (size in inch)

4.3 Software Testing Against Mill Measurement

Large number of the mill testing data was used to verify each of the developed software programs. In the Fig. 5, the predicted temperature profile based on the web-based finite-differential program was compared with the field measurement. Since the surface temperature was the only temperature data that could be measured in a production line, the predicted surface temperature was compared with the measured one. It shows from pass to pass the surface temperatures from prediction correlates very well with the measured ones. The point in the right end also confirms the good result for the controlled water cooling.

4.4 Object-Oriented Programming

All the mill applications were developed in the object-oriented principle. Logics and calculations for each web form were implemented in a separate class or maybe the parent class of it. The code inside the web form only called corresponding class for result supply. For all the programs in the metalpass.com, there is only one set of the code for strain calculation, spread prediction, and forward slip calculation, etc. There is no any code repetition.

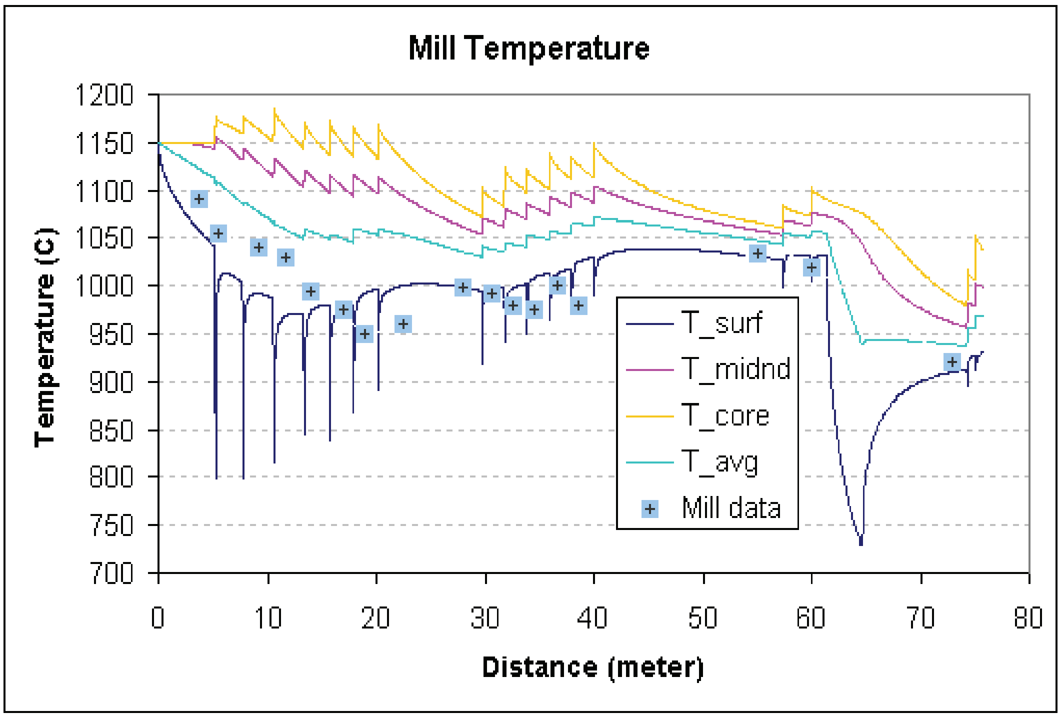

Fig. 5: Calculated temperature profile with comparison with the measured surface temperature

An excellent example to demonstrate the object-oriented feature is the suite for force/torque/power calculation [5]. Though there are nine pass sequences, almost all the calculations were done in a single class, the parent class that corresponds to the General pass sequence. Each of the eight derived classes only made minimal modifications to the parent class, primarily the cross-section and contact area.

4.5 Web-Related Handling

User-friendliness. Internet user often prefers simpler user interface than Windows program user. With large number of rolling process models integrated into applications, user only needs to enter minimal data, and some of which, such as roll gap and preferred fill ratio, can still be suggested by the program if user selects to. This greatly the improves program user-friendliness.

Intelligence. Intelligence is the key for the web-based design and development software. A web-based software should not simply serve as a tool for data processing and data management like many windows-based ones. The primary factor for the competitiveness of the internet mill-software should exist in the mill knowhow. The roll pass design programs hosted in the metalpass.com differentiates itself by high-level intelligence through applying large number of sophisticated models.

Calculation speed. Calculation speed and resource saving in the internet application is more critical than in the Windows application. With waiting time over 10 seconds or even less, the user would feel uncomfortable. With a relatively large website such as metalpass.com, with over 40,000 pages, the computing resource needs to be carefully managed. This is particularly the case for the temperature-profile prediction with finite differential method.

Data Management. Some users may have concern on the security of their data. Metal Pass' user agreement confirms that user's data is carefully protected and never revealed to others. In fact, most engineering applications in the metalpass.com store all the data in the user's computer, not in the web server. Therefore, no others except the user have access to the data.

SUMMARY

Complicated rolling mill process demands sophisticated models and software; good future-potential awaits web-based mill application.

A variety of web-based programs, some powerful and others easy to use, are available online as great tools for advanced mill design and development.

Highly accurate models and extensive mill-tests verified the high quality of the web-based mill applications. Web-related handling further improved the performances of the programs.

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