KVALI-METAL: A PROBABILITY MODEL TOOL FOR OPTIMIZING PRODUCT PROPERTIES IN THE STEEL INDUSTRY

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Abstract

Kvali-metal is a combination of an advanced modelling approach and a software tool. It provides an advanced probability-based approach to planning and controlling the properties of steel products. The most important part of the kvali-metal solution is fitting statistical models to the mean and variance of product properties with the aim of accurately predicting the statistical distribution of product properties. The models are then implemented into a software tool that is used to plan and control properties so that the disqualification probability given by the predicted statistical distribution is low enough. The proposed approach takes into account the dependence of variance on process variables, which enables more accurate prediction of probabilities and more effective minimization of rejections. The system has been implemented in Ruukki's plate mill and the tool has been found to be useful.

1 Introduction: The importance of property planning and control in steel production

The properties of steel products depend on the composition and thermomechanical treatments of the production process in a complex way. Customers often set requirements for the properties, and meeting of these requirements is controlled with systematic testing. A disqualification in these tests becomes expensive. Thus, modelling, planning and control of properties is important and commonly utilized by steel mills in many different ways in steelmaking and steel product manufacturing (Figure 1).

The usual approach to planning and control has been based on an approach where statistical regression-type models (like neural networks or linear models) are used to predict the properties [1]. These models are then utilized in software, which is used for many purposes, e.g. to determine alloying or to adjust rolling forces. However, it is usual that not only the mean but also the variance of properties depends on controllable process variables [2]. Thus, the above-mentioned usual modelling approach can not perfectly describe the conditional distribution of the response variable. Modelling is more exact when the dependence of variance on process variables is also taken into account: Variance and probability modelling enables more exact planning and control [3].

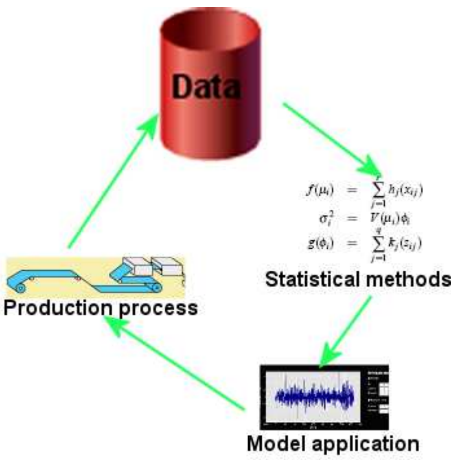

Figure 1: Statistical modelling has an important role in the planning and control of steel manufacturing processes.

In practical steel production there is always some variance and seemingly stochastic variability in the realized properties of steel products - exactly similar product properties are very difficult to reproduce. Minimizing variance in product properties is one of the main goals of quality improvement [4].

The purpose of planning and control is to minimize (or actually optimize) the number of products disqualified because of faulty product properties. Thus, in any case planning and control involve disqualification probabilities, at least unconsciously. Therefore, it seems feasible to base planning and control of product properties on disqualification probability: This approach provides several advantages:

- Working directly with probabilities and conditional distributions is always the most exact approach to planning and control - the commonly used simplification of examining only the expected value of distribution works if the distributional assumptions behind it are correct enough
- The variability in variance is automatically taken into account
- Doing planning and control with probabilities is easy and informative

This paper suggests an approach to planning and controlling product properties that is based directly on predicted disqualification probabilities. This novel approach is called 'kvali-metal'. The next sections describe the statistical models that are used to predict probabilities and the principles of the software interface by which means the models are intended to be utilized in steel production. A case implementation is also presented.

2 Statistical modelling of disqualification probability

Kvali-metal employs statistical models that predict the conditional distribution of a product property (Figure 2). In the model framework both the mean and variance depend on input variables.

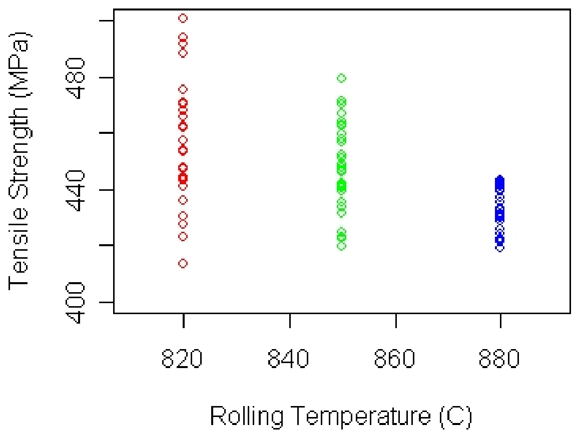

Figure 2: Kvali-metal employs statistical models to describe the dependence of variance on input variables. In the figure, both mean and variance decrease as temperature increases.

The general formulation of the model framework is:

$$\begin{aligned} y_i^* &= h(y_i) \\ y_i^* &\sim N(\mu_i, \sigma_i^2) \\ \mu_i &= f(x_i, \beta) \\ \sigma_i^2 &= g(x_i, \tau) \end{aligned} \quad (1)$$

Here y_i denotes the product property value and x_i denotes a vector of explanatory process variables related to the i th observation. It is assumed that some monotone transformation of response variable $y_i^* = h(y_i)$ is normally distributed with mean μ_i and variance σ_i^2. Possible transformations include identity $y_i^* = y_i$, log $y_i^* = \log(y_i)$ and Box-Cox $y_i^* = (y_i^\lambda - 1)/\lambda$ transformations. Both mean and variance are allowed to depend on process variables in an arbitrary, non-linear way. Possible methods for modelling these dependencies include neural networks, linear and non-linear parametric regression, support vector regression and additive models. For more details, see [5]. The most suitable modelling method and transformation are chosen in the model development phase.

To fit and develop the model, data on product properties and process variables used in planning and control must be collected. In the model development phase the data are split between training and validation with the purpose of finding a model with maximal real predictive performance.

Fitted models give predictions of the mean and variance of transformed-scale responses. The predicted mean in the untransformed scale $h^{-1}(\widehat{\mu}_i)$ is straightforward to calculate using the inverse function of $h(\cdot)$. Predictions of disqualification probability can be easily produced based on the assumption of normal distribution: Let $\{y : y < R_i\}$ be the disqualification region and $\widehat{\mu}_i$ be the predicted mean and $\widehat{\sigma}_i^2$ be the predicted variance. Then the disqualification probability is

$$P(y_i < R_i) = P(y_i^* < h(R_i)) = F\left(\frac{h(R_i) - \widehat{\mu}_i}{\widehat{\sigma}_i}\right) \tag{2}$$

where $F(\cdot)$ is the Gaussian cumulative distribution function. If the normal distribution assumption seems to be too coarse an approximation for probability prediction, it is possible to instead define $F(\cdot)$ to be the empirical distribution function of standardized residuals.

The $100(1-p)\%$ prediction interval for observation y_i is

$$\left[h^{-1}\left(F^{-1}(\frac{p}{2})\widehat{\sigma}_i + \widehat{\mu}_i\right), h^{-1}\left(F^{-1}(1-\frac{p}{2})\widehat{\sigma}_i + \widehat{\mu}_i\right)\right] \tag{3}$$

where $F^{-1}(\cdot)$ is the inverse cumulative distribution function. The normal 95 % prediction interval is obtained by using $F^{-1}(\frac{p}{2}) = -1.96$ and $F^{-1}(1-\frac{p}{2}) = 1.96$.

The most usual case is to employ identity transformation $h^{-1}(y) = y$. In this case, the predicted deviation of y_i is directly $\widehat{\sigma}_i$. Otherwise, the length of the prediction interval can be used as a measure of the deviation of y_i.

3 Utilization of probability models in planning and control

The principle of utilizing statistical models is the same in both planning and control: The models are employed to select the production method so that the disqualification probability is minimal or at least low enough compared with the costs of further decreasing the disqualification probability. The advantage of the proposed probability-based approach is that planning/control then directly aims at removing the most harmful variation, namely disqualifications (Figure 3).

The kvali-metal planning tool includes a user interface for simulating the effect of production method and process settings on product properties and the risk of disqualification. The idea is that the tool helps employees working with quality or product and production planning in their work. The tool can be used in several situations, for example:

- production runs: selecting composition and treatments for castings
- customer orders: planning the manufacturing method for each order, handling of non-standard customer requests
- products: determining the allowed production methods and recommended process settings for each product

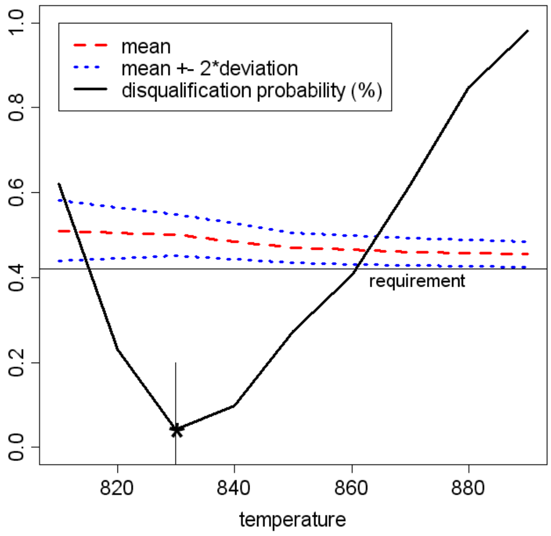

Figure 3: Kvali-metal model finds the process settings that minimize the risk of product properties failing to meet their requirements.

The kvali-metal control tool may include a user interface or it may work as a silent application. The software receives process measurements as the process goes on and the models use the data to predict the distribution of product properties in real time. There are two different uses for the control tool: adaptive control adjusts the process settings based on the prediction, and detective control just alerts when the predicted rejection risk is too high.

The advantage of adaptive control is that corrective actions are automatically attempted if the predicted risk seems too high. The process settings may be adjusted automatically or via the user interface by using the information about the predicted product properties and related disqualification probability.

A control application that instantly gives a notice if the risk of disqualifications is increased can also be very useful in some cases. When problems are detected early enough, there is a possibility and time to react and correct the problem before significant economical losses ensue.

Small variance in product properties is often considered equivalent with good quality. An important aim of quality improvement is to decrease variation in properties. Understanding the dependencies between variance and process variables is very helpful in controlling and decreasing deviation. Variance modelling is an excellent tool for improving understanding about the reasons affecting deviation.

The use of the kvali-metal approach in planning and control decreases variation in product properties directly, and the kvali-metal planning tool can be used to search for production methods with lower deviation. The developed models of variance can also be utilized to find ways to decrease variance in a single data analysis effort without implementing any tools. Thus, it is meaningful to say that the primary benefit of kvali-metal is improved production efficiency resulting from reduced variation in product properties (Figure 4).

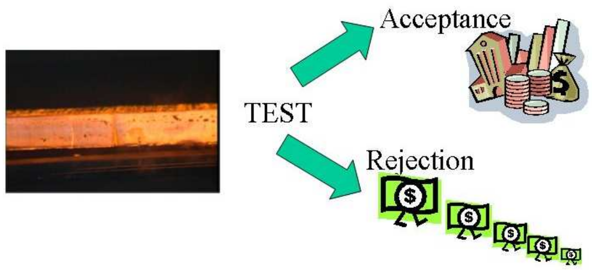

Figure 4: Probability-based planning and control aims for economic savings by minimizing the number of disqualifications.

4 Case implementation: Planning the mechanical properties of steel plates

Kvali-metal tools have been implemented at Ruukki Production, Raahe Works. Statistical prediction models were fitted to predict the acceptance probability in tensile testing of low-alloyed hot rolled steel plates with a mainly ferritic-pearlitic microstructure. Regression models were fitted to predict the conditional distribution of tensile strength, yield strength and elongation. It turned out that the variance in mechanical properties depended on about 12 process variables related to the composition of steel and thermomechanical treatments. For example, microalloying has a non-linear effect on variance in strength, and the magnitude of the effect depends on the rolling method.

The developed models were implemented into a planning tool used by product designers. The user interface of the planning tool provides a user interface for simulating the effect of composition and thermomechanical treatments on product properties. With the planning tool, the effect of alloying on disqualification probability is easy to see and take into account.

The tool has been in everyday use for a couple of years and its users have considered it a major improvement. The improved quality of mechanical properties has yielded economic benefits. For more details on the application, see [6]. The approach is currently also being adopted for purposes other than product planning: different models and a tool for utilizing them were recently developed for the purposes of production planning.

5 Discussion: The generalizability of the approach

The case implementation is for the mechanical properties of low-alloyed steel plates. The success of the case example indicates that the same approach would also be applicable for other steel products. The same benefits could be realized in many other plants, also. It seems obvious that the same approach would also work for steel properties other than strength and ductility, for example toughness, hardness, surface quality, thickness and flatness could be possible. Furthermore, generalization of the approach to other metal industries and even to other manufacturing industries is straightforward. The advantages of variance modelling and probability-based planning remain the same in all industries: only the properties being predicted and the process variables being planned and controlled change.

The case implementation is for advance planning of properties. However, statistical prediction models are also often utilized in real-time control of product properties. More exact models enable more effective control. Thus, utilization of the kvali-metal variance modelling approach is suggested to offer benefits also in control problems. Working with predicted disqualification probability should be the most effective way to quickly find and then prevent situations with a high risk of failing and to minimize disqualifications.

6 The implementation steps

The proposed probability-based approach, kvali-metal, is applicable in planning and controlling a product property if the following prerequisites are satisfied:

- Products place some requirements on the property - failure to satisfy these requirements is a drawback
- Measurements of the property are continuously distributed, i.e. the property is not measured on a nominal scale
- There are some controllable variables that affect the property
- Data on the property and the variables needed to plan or control the property are available

Implementation of kvali-metal as a planning tool (Figure 5) or as control software consists of the following steps

1. Preliminary modelling is done to examine the distribution shape and magnitude of variance variability in the product properties
2. The results of the preliminary study are analyzed to employ rationale assumptions and modelling methods in the next step
3. Models for predicting the mean and variance of the product properties are developed with the purpose of accurately predicting the disqualification probability

4. Models and the required data communications are implemented into software. If needed, a user interface is also developed.

			Tensile strength	Yield strength	Elongation	
Requirement-MIN			485	345	20	
Requirement-MAX			620	-	-	
Predicted mean			495.2	389.3	26.53	
Predicted deviation			6.5	10.6	2.32	
Disqualification probability			0.02	0.0003	0.0001	
			Check	OK	OK	
Thermomechanical treatments			T1	T2	T3	T4
			-	3	N	0
Composition				5		0
C	Mn	Si	Al	Nb	Ti	V
0.11	0.45	0.6	0.03	0.01	0.01	0.002
	0.2	0.25				
0.12	0.5	0.75				

Figure 5: The user interface of kvali-metal tools is tailored to simulate the effect of source information on the disqualification probability.

7 Conclusion

The kvali-metal solution consists of three parts: development of statistical models for the distribution of product properties, analysis of reasons for variance variability in product properties and implementation of developed models into a software tool. The study suggests that kvali-metal may be used to improve the quality of different product properties in many kinds of processes.

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