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# IMPLEMENTATION OF A NEW TECHNOLOGY FOR QUALITY IMPROVEMENT AND PRODUCTIVITY ENHANCEMENT OF LONG PRODUCTS[1]

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**Abstract**
A new technology has been developed for production of superior quality bars and rods. The aim is to predict and control accurately the product properties during actual processing stage itself, rather than post-production 'product-testing' stage (as is presently practised). The new technology capitalizes on the methodology that combines 'advanced microstructural engineering' and the state-of-the-art 'data mining' techniques such as Artificial Neural Networks (ANN) to assess microstructure and product properties. Danieli QTB PLUS System based on this technology was implemented in Riva Group; at two of their rebar mills in Europe – one in Verona (Italy), and another in Seville (Spain). The system ensures superior quality and uniformity of product, as mentioned in customer order. This has improved hit rate and reduced downgrades. This reduces the need for extensive material sampling and testing, and thereby, improves cycle time and productivity. The technology is also useful for process optimization and design of new product. This reduces product development cost, and improves resource utilization.
**Keywords:** Process control; Mechanical properties; Hot rolled bar.

## IMPLEMENTAÇÃO DE UMA NOVA TECNOLOGIA PARA A MELHORIA DA QUALIDADE E PRODUTIVIDADE DE PRODUTOS LONGOS

**Resumo**
A nova tecnologia foi desenvolvida para a produção de barras e fio máquina de qualidade superior. O objetivo é prever e controlar com precisão as propriedades do produto durante o processo em si, ao invés do controle de pós-produção e teste de produto (como é praticada atualmente). A nova tecnologia capitaliza a metodologia que combina tecnicas avançadas de engenharia microestrutural e o estado-da-arte em técnicas de banco de dados, como Redes Neurais Artificiais (ANN) para avaliar a microestrutura e propriedades do produto. O Sistema Danieli QTB PLUS baseado nesta tecnologia foi implementada em Grupo Riva, em duas de suas fábricas de vergalhões na Europa - uma em Verona (Itália), e outra em Sevilla (Espanha). O sistema garante qualidade superior e uniformidade do produto, conforme mencionado no pedido do cliente. Isso melhorou a taxa de acerto e reduziu processos de desclassificações de qualidade. Isso reduz a costante necessidade de amostragem e ensaio, assim, melhora o tempo de ciclo e produtividade. A tecnologia também é útil para otimização de processos e desenvolvimento de novos produtos. Isso reduz o custo de desenvolvimento de produto, e melhora a utilização dos recursos.
**Palavras-chave**: Controle de processo; Propriedades mecânicas; Laminação a quente de barras.

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## 1 INTRODUCTION

In bar and rod mills, the product quality is known only after the product is tested, but not before. This is a conventional practice. Such 'post-mortem' test on 'dead bar' gives information only on whether or not the product is good enough as per customer requirement. Clearly, the outcome of such testing is either accept or reject the product. The rejected bars are taken out from primes and are sold as seconds at much reduced price. One inherent drawback of such testing practice is that there is no way any corrective action can be made in the product if the mechanical property of some or all bars in a lot are found inadequate.

A construction pillar is as strong as the weakest section of the bar or the weakest of all rebars used to build the pillar. Thus strength of construction pillar depends on minimum available strength. Also, important is the UTS/YS ratio of the rebars for seismic resistance. Thus, not only adequate strength but also strength uniformity among rebars is important apart from bendability and weldability. Hence, selection of rebars for construction pillars is very important; even more so for earthquake-prone regions of Alaska, Puerto Rico, Chile, and Mexico.

To produce steel of high quality, the properties of products should be known during the actual processing stage itself, and not any after. Knowing product quality before hand has two advantages. First, any deficiency in quality in any part of the bar can be corrected during the processing stage itself, so that only prime grade steel can be produced. Second, the product uniformity can be ensured through minimum variability of properties among the bars in a lot.

With this pretext it is essential to estimate some way the mechanical property of bars during actual rolling stage first. Fortunately, physically based metallurgical models are quite useful for this purpose. These models can track the thermomechanical histories; and thereby, the microstructural events of recovery, recrystallization, grain growth and phase transformation. The final microstructure can, therefore, be predicted based on processing conditions. Once the final structure is known, the mechanical properties can be correlated with the structure. The final microstructure and mechanical properties of bars can be verified through metallographic findings, and mechanical testing results.

One drawback of using these physically based metallurgical models is that they can predict the average strength levels of steel grades. While this is useful for new product development, and process design, the requirement of steel mill to maintain quality of product is even more challenging. This would require that the properties of each and every bar should be predicted with high accuracy. Thus, the existence of product-by-product variation of properties within a batch of single steel grade of rolled products are required to be distinguished. This is a formidable task, and requires the process uncertainties to be captured and modelled around the physically based metallurgical models. Here, the use of 'Data Mining' based models such as Artificial Neural Network (ANN) prove very effective [1].

Danieli has developed and implemented such an integrated model combining the merits of physically based metallurgical models and Artificial Neural Network. This integrated model is used at the 'heart' of the Advanced Quenched and Tempered Bar (QTB PLUS) system to predict and control the property of bars, and to improve the productivity [2,3]. The system was implemented in the steel-giant Riva Group's two Bar and Rod Mills at two different locations – one at Verona (Italy) and another at Seville (Spain) [4]. The systems showed excellent results in terms bar-to-bar assessment of properties. With the real time availability of information regarding the

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product properties, high product quality is achieved through realtime control. This ensures strength requirements and uniform property requirements. With accurate assessment of mechanical properties, the need for sampling and testing is reduced. This improved productivity and reduced cost, and cycle time. The present paper discusses about the online model development, system implementation , and real-time performance of DANIELI-QTB PLUS system in the Bar and Rod Mills of Riva.

## 2 MODEL DEVELOPMENT

Figure 1 shows a series of physically based metallurgical models and interactions between them. Each model is interlinked with another with a set of input and output. The figure shows the way mechanical property is estimated using a set of models. These models are described below.

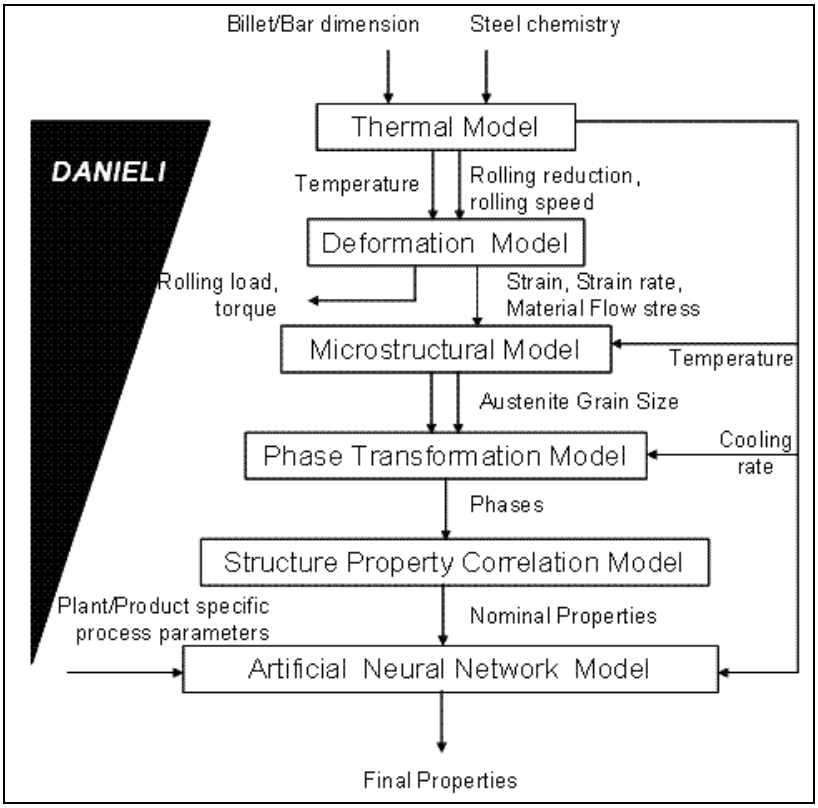


**Figure 1:** Interaction between models for prediction of mechanical properties.

### 2.1 Thermal Model

In case of bar & rod rolling, billets are heated in the reheat furnace and are rolled through a sequence of roughing, intermediate, and finishing mills. Once rolling is complete the bars are water quenched with high pressure water jets in the waterbox, and are finally allowed to cool on the cooling bed. The thermal simulation of rolling process involves one dimensional heat transfer modeling. The governing equation is developed in cylindrical coordinate system.

$$\frac{\partial}{\partial r}\left(k\frac{\partial T}{\partial r}\right)+\frac{k}{r}\left(\frac{\partial T}{\partial r}\right)+q_{TR}=\rho C\ \frac{\partial T}{\partial t} \qquad (1)$$

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where $q_{TR}$ is the heat released due to the transformation of austenite to other phases (i.e. ferrite, pearlite, bainite or martensite). The model incorporates temperature dependent thermal conductivity and specific heat at various phases.

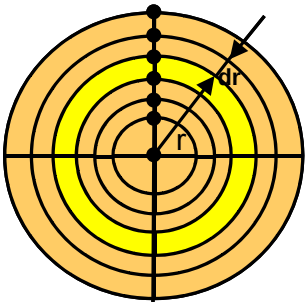


**Figure 2**: Solution domain for finite difference scheme in a bar.

Although the quenching with high-pressure water jets from the nozzles remove large portion of the heat from the outer surface of bar, heat loss in air on cooling bed is also substantial. As a result the overall heat loss ($q_{ov}$) has been calculated taking both radiation and convective mode of heat transfer into consideration.

$$q_{OV} = q_C + q_R = h_{RC}\left(T_s - T_A\right) \qquad h_{RC} = \sigma R\varepsilon\left(T_S^2 + T_A^2\right)\times\left(T_S + T_A\right) \qquad (2)$$

where $h_{RC}$ is radiative-convective heat transfer coefficient. R is radiation factor, comprising the emissivity of steel and the relative geometry of material. ‘σ’ and ‘ε’ are Stephan-Boltzman constant, and emissivity of rod respectively. $T_S$ and $T_A$ represents the surface temperature of bar, and the atmospheric temperature (in K) respectively. The combined heat transfer coefficient has also been used by other authors [5].

### 2.2 Deformation Model

The model calculates the flow stress of the material inside the roll gap based on the rate of rolling deformation and the deformation temperature during deformation [6]. Rolling load is then calculated from the knowledge of roll gap geometry, the mean flow stress ($\overline{\sigma}'$), and the inhomogeneity of the rolling process.

$$\overline{\sigma}' = f\left(\varepsilon, \dot{\varepsilon}, T\right) \qquad (3)$$

Deformation model provides total equivalent strain, and strain rate. These are important inputs to the microstructural model. Apart from these, it calculates rolling load, and torque, which can be validated with the actual plant measurement [6].

### 2.3 Microstructural Model

In rod rolling, austenite grains are subjected to dynamic, metadynamic and static recrystallisation during rolling and interpass annealing [7]. The fraction recrystallised (X) follows the Avrami equation.

$$X = 1 - \exp\left[-0.693\left(\frac{t}{t_{50}}\right)^n\right] \qquad (3)$$

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The kinetics of recrystallisation is expressed through $t_{0.5}$ which is the time for 50% recrystallisation and depends on prior deformation, deformation temperature and initial microstructure. 'n' is material constant.

### 2.4 Phase Transformation Model

During quenching the surface temperature of bar is brought below the $M_s$ temperature, and an uniform martensitic rim is formed. As the bar comes out of quenching section, heat from center of the bar flows from core to rim. The martensite subsequently gets tempered, and tempered martensitic ring forms. Various sections within the bar undergo different cooling rates; as a result, different phases form between the core and the rim. The microstructure of the bar consists of a tough core, comprising ferrite, pearlite, and sometimes very little bainite; and tempered martensitic rim. In between these two regions there exists bainite rich area, as shown in Figure 3.

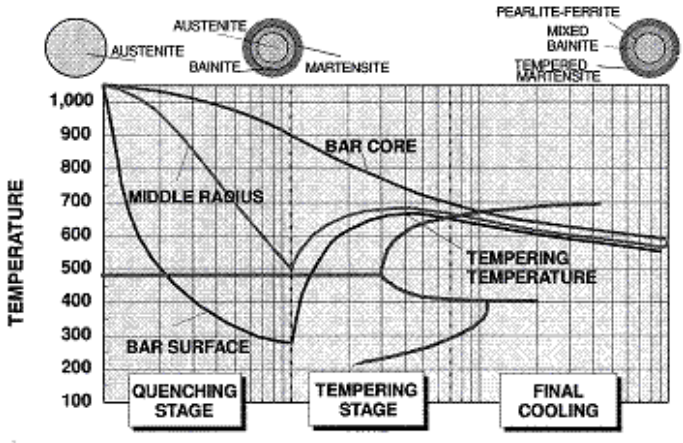


**Figure 3**: Quenching and self-tempering.

The kinetics of transformation follows the Avrami equation where *k* and *n* are material constants [8].

$$X = 1 - \exp\left(-kt^n\right) \qquad (4)$$

### 2.5 Property Correlation Model

The Property model relates the structure with mechanical properties. With knowledge of ferrite grain size, volume fractions of different phases, size and volume fraction of precipitates the mechanical properties are estimated. The model relates property with UTS, EL, and hardness of the material. As discussed earlier, the properties obtained from this model gives nominal value. For, bar-to-bar prediction of properties, ANN model is integrated with metallurgical model.

### 2.6 Ann Model

The feed-forward network with a hidden layer of neurons in between the input and the output layers is found suitable for prediction of mechanical properties. The network is trained using the Back-Propagation (BP) algorithm. The best network topology has been identified by comparing the selection (validation) performance of a

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set of networks with different configurations where the lowest error between actual mechanical properties and predicted values are obtained. Thus, the best network is selected with highest level of accuracy with largest value of coefficient of determination

The above models are interconnected in the way shown in Fig. 1. The integrated model is then used as the 'core' around which the QTB PLUS system was developed incorporating technology to access real-time input and deliver real-time output.

## 3 SYSTEM IMPLEMENTATION

### 3.1 Riva, Verona (Italy)

The QTB PLUS system was implemented for the steel giant Riva Acciaio, Italy, at their Bar and Rod Mill in Verona. The plant layout used for the mill is of the 'returning' type for economy of space (Fig. 4). The mill produces bars typically of diameters between Φ 8 and Φ 32 mm in steps of 2 mm. The steel grades produced are B450C and B500C, according to the normative UNI ENV 10080 for rebars. The Roughing stand exit temperature is about 1050 – 1080°C. The end rolling temperature is about 1080 – 1100°C. The final rolling speed is 30 m/s (for the smallest diameter bar of Φ 8 mm), and 6 m/s (for largest diameter bar of Φ 32 mm). In the Bar Mill slit rolling may be applied to smaller diameter bars of Φ 8 - 12 mm to improve productivity.

The QTB PLUS system was implemented in January 2009. Since then the model has been predicting the mechanical properties in real time. There has been no failure reported so far regarding the functioning of the models. The mechanical properties are predicted on bar-to-bar basis. The uniformity of properties of rebar in a batch is ensured through proper control of quenching process.


**Figure 4**: Control parameters for mechanical properties.

The control of the quenching process is done through the adjustment of water pressure and flow rate depending on the bar diameter, finish rolling temperature, end-quench temperature, and rolling speed (Fig. 4). This ensures higher quality.

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### 3.2 Riva, Seville (Spain)

QTB Plus system was implemented in Riva's Bar and Rod Mill at Seville, Spain, in August 2009. The layout of the mill is shown in Fig. 5. It has 4 vertical roughing stands, 8 intermediate stands with horizontal and vertical orientation, and 4 finishing stands. It produces rebars of diameters Φ 16, 20, 25 and 32 mm.


**Figure 5**: Control parameters for mechanical properties.

The line is equipped with slit rolling and is practiced for bar of diameter Φ 16 mm. The final rolling speed is 20 m/s (for the smaller diameter bar of Φ 20 mm), and 6 m/s (for larger diameter bar of Φ 32 mm).
The steel grades produced are B400SD and B500SD, according to the normative UNE 36065 EX for rebars. The rebar is mainly of low carbon steel with C 0.18 – 0.24, Mn 0.6 – 0.8, and Si 0.15 – 0.3 by wt. The carbon equivalents are around 0.4. The YS and EL are more than 500 MPa and 8 % respectively. The UTS/YS ratios are more than 1.15.

## 4 RESULTS

In order to show the accuracy and reliability of the implemented model a rebar of diameter ϕ 24 is chosen as an example. Table 1 shows the steel chemistry of the rebar. The carbon equivalent is also shown.

**Table 1**:Chemistry of Φ 24 mm TMT rebar (% by wt)

| C | Mn | Si | Cr | Mo | V | Ni | Cu | S | P | *CEQ* |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.195 | 0.8 | 0.27 | 0.068 | 0.015 | 0.001 | 0.081 | 0.026 | 0.038 | 0.021 | *0.37* |

Figure 5 shows the typical controlled cooling setting for ϕ 24 mm. The initial nozzles at waterbox are activated for proper cooling control of rebar. Fig. 6 shows temperature evolution at different annular sections of rebar during water quenching and subsequent air cooling. As can be seen, although temperature gradient exists between center and surface before cooling, the temperature becomes nearly uniform at all sections after cooling. The bar center temperatures before and after quenching are 1075 °C and 650 °C respectively.

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Figure 7 shows volume fraction of different phases at different annular rings. From this it calculates the distribution of volume fraction across the bar radius. The structure at the centre is ferritic-pearlitic with 70 percent ferrite, and 30 percent pearlite.

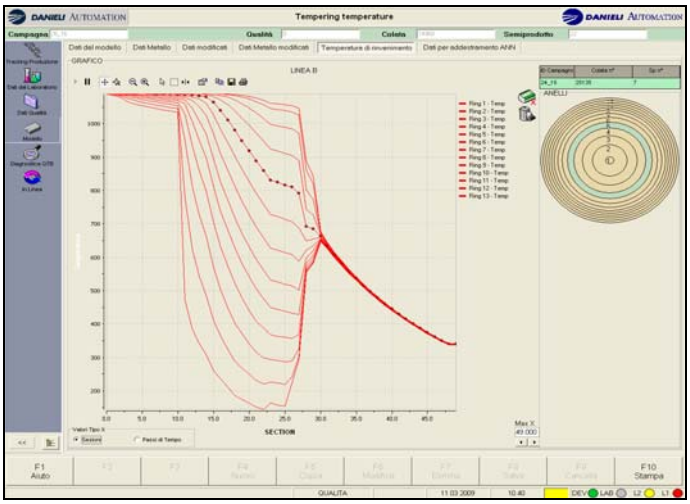


**Figure 6:** Temperature distribution at different annular sections of bar during and after quenching.


**Figure 7**: Distribution of different phases along radius of the bar.

## 4.1 Testing And Validation

Figure 8 shows the volume fraction of different phases across section of ϕ 24 mm. From these, the mechanical properties such as YS, UTS, HV10 are calculated. These are also shown. These properties were then predicted with actual measured values from metallographic study.

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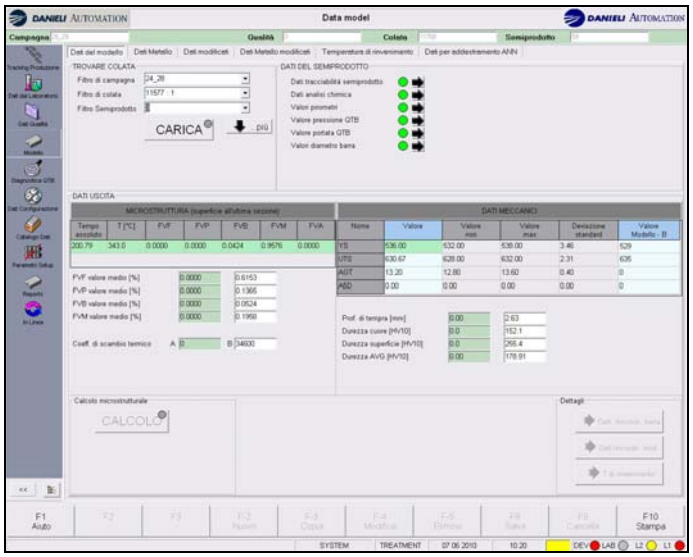


**Figure 8**: Prediction of microstructure and properties of rebar.

Figure 9 (a) shows the microstructure at the core and the rim of the rebar. This is obtained through metallographic examination of ϕ 24 mm rebar. It shows the rim thickness of the bar. To verify the hardness profile, microhardness test was carried out, and the values at different positions are plotted in Figure 9 (b). The hardness profile predicted from the QTB PLUS system is also plotted for comparison. A good match is obtained at all locations across thickness. The rim thickness predicted by the system matches well with that obtained from metallographic examination.

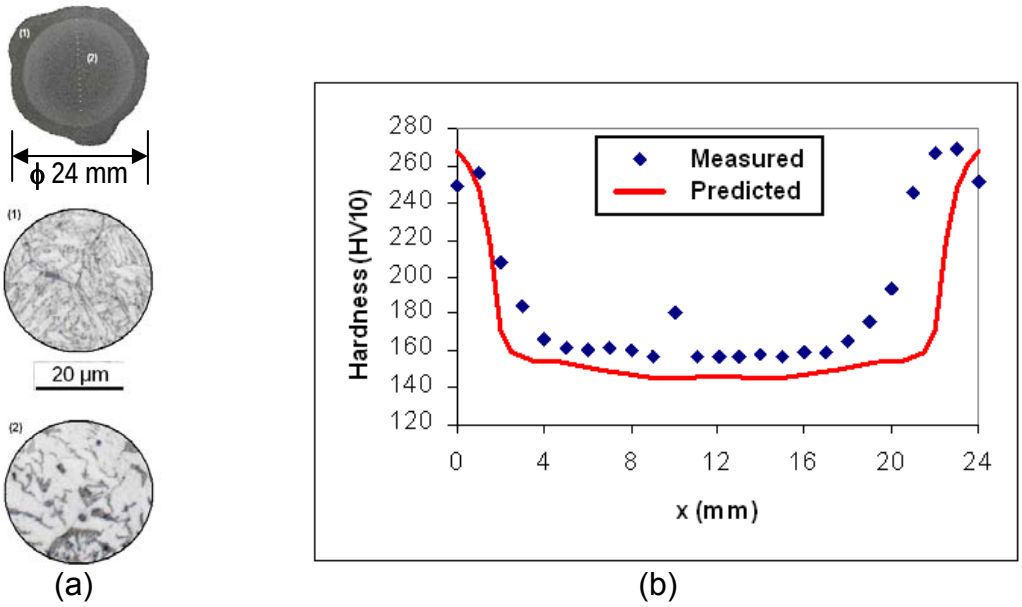


**Figure 9**: Comparison between Actual and Predicted Structure & Properties of Φ24 mm rebar - (a) Microstructure; (b) Hardness

## 4.2 Accuracy & Reliability

To determine the accuracy and reliability of the system 136 rebar samples were taken between diameters Φ 8 – 32 mm for comparison between predicted and actual

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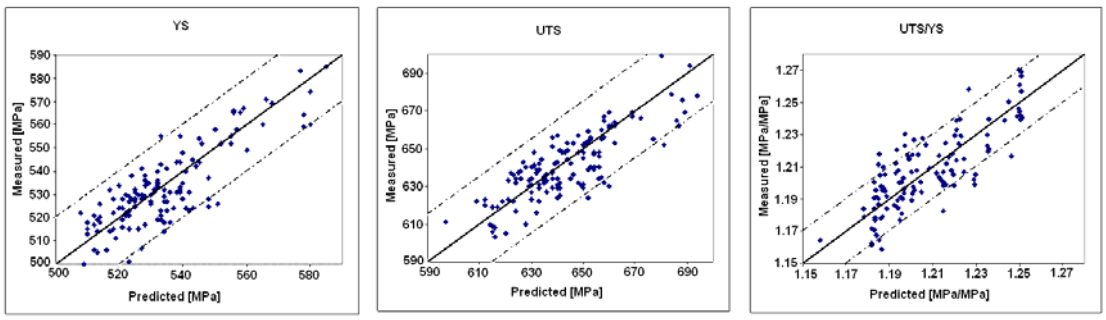
mechanical properties. This involves rebars from both the mills. The rebar samples are of low carbon steel with C 0.18 – 0.24, Mn 0.6 – 0.8, and Si 0.15 – 0.3 by wt. The carbon quivalents are around 0.4. The YS and EL are more than 500 MPa and 12% respectively. The UTS/YS ratios are more than 1.15. The actual properties of these samples are measured on servo-hydraulic mechanical testing machine at the plant Testing Laboratory.

The measured values of YS and UTS are then compared with the QTB PLUS system predicted ones (Figure 10). The data covers YS range of 500 – 590 MPa, and UTS range of 610 – 700 MPa. Figures 10 (a) & (b) show the comparison between the actual and predicted YS. A good match is obtained in both cases. The dotted lines show the limits within which majority of the points lie. It can be seen that majority of the points fall within ± 20 MPa for YS and ± 25 MPa for UTS. Figure 10 (c) shows the comparison between actual and predicted UTS/YS ratio. Again a good match is observed with the limits of ± 0.02.




(a) (b) (c)

**Figure 10**: Comparison between Actual vs. Predicted values of (a) YS, (b) UTS , and (c) UTS/YS.

The standard deviations obtained from the predicted errors of YS and UTS are ± 9.57 MPa, and ± 11.32 MPa respectively. In case of UTS/YS ratio, the standard deviation is ± 0.019.

## 5 DISCUSSION

An important aspect of such predictive systems that are used for the purpose of controlling microstructure and properties is that of sensitivity. It shows the capability of the system to respond against the change in process variables.

Figure 11 shows the sensitivity of quench parameters on final rebar temperature as predicted from QTB PLUS. As can be seen, significantly different water quantities are required to quench smaller and bigger size rebar (Figure 11b). The change in water pressure shows larger variation in cooling bed temperature for larger than smaller diameter rebar. While it is true for flow rate, the rate of drop is more sensitive to flow rate than pressure.

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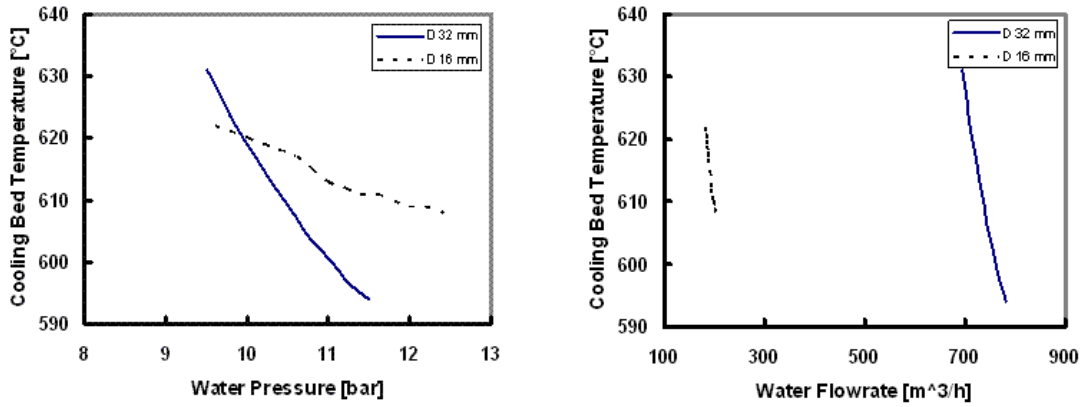


(a) (b)

**Figure 11** : Quenching Sensitivity – (a) Φ16 mm, and (b) Φ 32 mm.

### 5.1 Benefits

Apart from prediction and control of bars, Danieli QTB PLUS System is useful to produce desired mechanical properties as specified by the customer in the order. For any given final strength of the bar, the system calculates process set-up parameters. Thus, the system predicts, controls and also ensures mechanical properties of the bars in real time. The assessment of properties helps proper monitoring, and helps to reduce the sampling size for mechanical testing. This reduces cost and improves productivity. The system can be used to design new grades of bar with superior quality such as improved weldability, elongation, and bendability. It helps perform process optimization and parameter design. Table 2 shows the potential benefits of the system.

*TABLE 2 : Benefits of DANIELI-QTB-PLUS*

| BENEFIT | TYPE |
|---|---|
| Product Certification | * Automatic certification & generation of test certificate<br>* Reduction of Sampling, Testing<br>* Product Acceptance Testing |
| Product Development | * Rationalisation of Steel grade<br>* New market development |
| Quality Assurance | * Ensures desired quality |
| Process Optimization | * Minimise use of resources such as fuel, water etc.<br>* Reduce Process Cost |
| Process Control | * Improve product quality |

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## 6 CONCLUSIONS

A new technology is developed in order to improve and control quality of rebars by integrating metallurgical models with Data Mining based Arificial Neural Network model. Danieli QTB PLUS is developed based on this technology. The system is implemented in two Bar and Rod Mills of Riva. The system is working steadily, accurately, and reliably without any problem since installation and commissioning. The system generates benefit to customers through product certification, new product development, quality assurance, quality optimization and process control.

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