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METALLURGICAL RESEARCH THROUGH IMPLEMENTATION: A NEW TECHNOLOGY FOR SUSTAINABLE PRODUCTION OF SUPERIOR QUALITY HOT ROLLED COIL[1]

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Abstract
The microstructural phenomena of recovery, recrystallization, precipitation, grain growth and phase transformation during thermomechanical processing of steel, are applied to estimate of final microstructure of steel strips, produced through hot rolling in a hot strip mill. A set of mathematical models is developed to simulate these behaviors and the final microstructure, and to assess the mechanical properties therefrom. The aim to develop a suitable technology to control the product properties during actual processing stage itself, and that too over the whole length of a coil, rather than post-production product-testing stage for a single sample from one end of coil (as practiced worldwide today). Thus, the new technology exploits the 'advanced microstructural engineering' to provide solution for a problem the world faces today – how to maintain uniform mechanical properties over the entire length of a coil, especially important for microalloying grades used for gas pipelines and automotive applications. An innovative approach is undertaken to combine the above set of physical metallurgical models with a data driven Artificial Neural Network Model to include process uncertainties into the final assessment of mechanical properties. Danieli CQE (Coil Quality Estimator), based this approach, was implemented in the United Metallurgical Company (OMK), at Vyksa, Russia - one of the largest pipe manufacturers of oil and gas pipelines for arctic applications. Danieli CQE ensures uniformity of mechanical property over the length of a coil, and thereby reducing downgrades. The system is applicable for low, medium, high carbon, and microalloying grades. Apart from ensuring superior quality product, it is very useful to identify the appropriate process window for development of new products. It is also useful for process optimization, and to ensure minimum utilization of energy and resources including expensive ferroalloys to produce any given grade of hot rolled coil.
Key words: Thermomechanical processing; Modeling;Physical metallurgy; Process control; Mechanical properties; Hot rolled strips and coils.

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1 INTRODUCTION

In a hot strip mill (HSM), the hot rolled coils are produced from slabs through hot deformation and subsequent cooling in water on a Run-Out Table (ROT). In conventional rolling, the starting slab thickness is about 210-250 mm. On the other hand, in thin slab casting and rolling, the starting slab thickness is about 50-90 mm. In both cases, the slab is then subjected to a sequence of passes to reduce its thickness down to about 1.0 - 18 mm. After all the rolling deformations are complete, the strip is cooled in water, and the huge length of strip (1.5-1.7 km!) is coiled in a downcoiler to produce the final product. Before final dispatch to customer, the coils are tested for requisite mechanical properties of yield strength (YS), tensile strength (TS), elongation (EL), and hardness (HV). This is done through mechanical testing of a sample from the coil. Such a sample is taken from the outer wrap of the coil, along the transverse direction. Once the sample is taken, it is allowed to cool from coiling temperature (about 600 ºC) down to room temperature. From the sample, a tensile testing specimen is then prepared, which is then tested on a servo-hydraulic tensile testing machine. The mechanical properties, obtained from the testing, are required to be posted on the test certificate for the customer before the coil is set for dispatch.

This is the conventional procedure for the testing and certification of a hot rolled coil, practiced worldwide. The procedure, however, has two drawbacks. The first, only one sample is usually tested per coil. And the second, the sample is taken from one end of the coil. Such a sample may not truly represent the entire length of a coil. Research literature reports plenty of the fact that there exists significant variation of mechanical properties over the length of a coil. This lack of uniformity of properties is found to be more significant in case of microalloyed steel than low carbon unalloyed steel. A variation of yield strength as much as 100 MPa along length of microalloyed strip has been reported in the literature.(1) Finally, such mechanical testing is done on a ‘dead coil’, i.e., after the coil is manufactured. Since no corrective action can be taken if some portion of a coil is found deficient in property, such testing procedure may be suitable for acceptance testing. But ensuring uniformity of mechanical properties along length requires on-line prediction and control. At present, no such system exists that can reliably predict and control properties of strip in real time with sufficient accuracy.

With the motivation to design and develop such a system, Danieli embarked on a project called the “Coil Quality Estimator (CQE)”, based on the fundamental research in the area of microstructural engineering to predict mechanical properties from the final microstructure after rolling and cooling. The system was developed, validated in Beta Steel, Indiana, and implemented at the United Metallurgical Company (OMK), Russia. High performance is maintained in terms of accuracy and reliability of the system. The benefit is derived through automatic product certification, design of new product development, optimization of processes, and development of superior quality coil. The present paper discusses on the method of development of such a system from the basic metallurgical research, implementation of the system, its performance, and benefits.

2 MATEMATHICAL MODELS

In CQE, the mechanical properties are estimated with the aid of a family of interconnected, physically based models. These models simulate the thermomechanical processing situation at each segment of the strip. Different models

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– Thermal, Deformation, Microstructural, Phase Transformation, Precipitation and Property Models – together form the CQE Mathematical Model Suite (Figure 1).

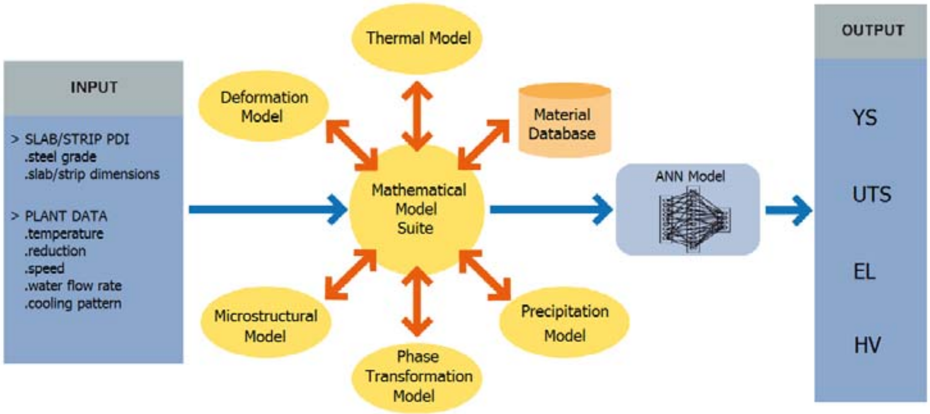

Figure 1. Flow chart for prediction of mechanical properties of steel

2.1 Thermal Model

To simulate thermal behavior of the strip a one-dimensional finite difference heat transfer model has been developed.

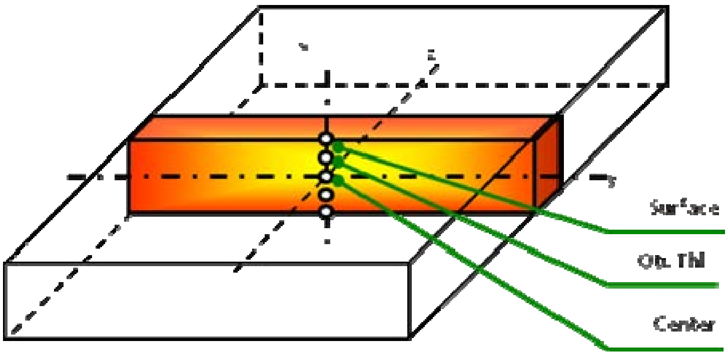

Figure 2. One-dimensional heat transfer model

The temperature evolution (T) over time (t) for any given point (x) inside the strip through the thickness (Figure 2) is then governed by:

$$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} + \dot{q}$$

The model takes into account the heat generation due to deformational heating, which increases temperature of strip. Heat transfer depends on the thermal properties of the strip material – thermal conductivity (k), specific heat (c), and density (ρ). These properties are temperature dependent. During rolling, as the surface of the strip comes in contact with the roll the surface temperature drops suddenly due to the 'roll chill effect'. When the strip comes out of the roll gap the surface temperature increases due to recalescence by the conduction of excess heat from the center to the surface of the strip.

After rolling, the strip is cooled in laminar water on the ROT. Here the strip is subjected to various modes of heat transfer - cooling in air due to radiation and convection in the region between the exit of the last finishing mill and the first water bank, and also between the last water bank and the downcoiler; cooling of strip under the laminar jets due to convection; and heat conduction within the strip. Boiling heat transfer phenomenon (Figure 3) is considered in the model with heat transfer coefficient defined as a function of the surface temperature of strip.(2)

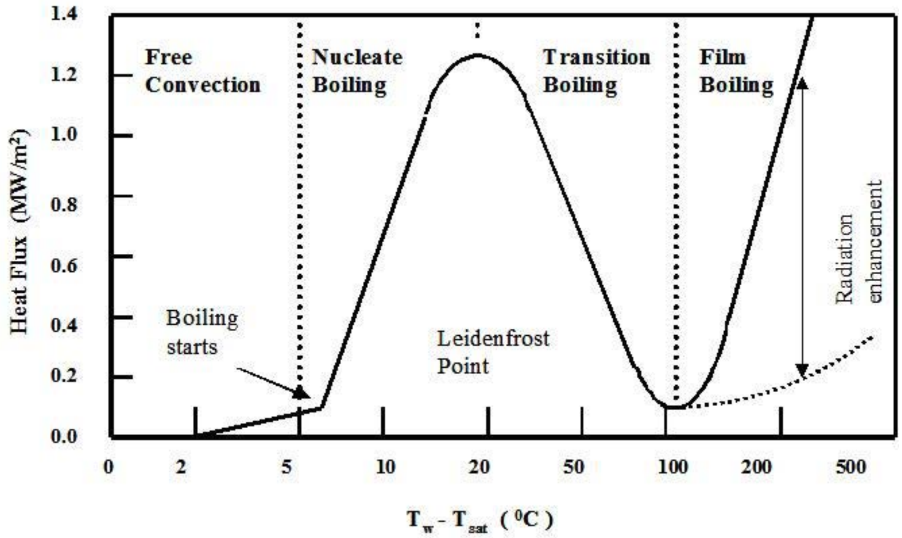

Figure 3. Boiling Heat Transfer on ROT

2.2 Microstructural Model

During reheating the precipitates of carbides and nitrides, already present within the cast slab, dissolve in the solid solution. In case of aluminium-killed steels the presence of fine aluminium nitride (AlN) particles pin the grain boundaries and resist abnormal grain growth of austenite.
The austenite grains are subjected to static and dynamic recrystallisation during rolling and interpass annealing. The fraction recrystallised (X) follows the Avrami equation.

$$X_{SRX} = 1 - \exp\left[-0.693\left(\frac{t}{t_{0.5SRX}}\right)^{n}\right] \quad \text{(static recrystallization)}$$

$$X_{DRX} = 1 - \exp\left[B\left(\frac{\varepsilon - \varepsilon_c}{\varepsilon_p}\right)^{k}\right] \quad \text{(dynamic recrystallization)}$$

The kinetics of recrystallisation is expressed through $t_{0.5SRX}$ which is the time for 50% recrystallisation and depends on prior deformation, deformation temperature and initial microstructure. 'n' is material constant. Dynamic recrystallization takes place if the accumulated strain ε exceeds a critical strain ε_c. B and k are material constants.

2.3 Deformation Model

The model calculates the flow stress of the material inside the roll gap based on the rate of rolling deformation, the temperature during deformation and the fraction recrystallized X_{RX}.

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$$\overline{\sigma}' = f(\varepsilon, \dot{\overline{\varepsilon}}, T, X_{RX})$$

Rolling load per unit width (P/w), is then calculated from the knowledge of roll gap geometry, the mean flow stress (σ'), the deformed roll radius (R'), Δh is the draft.[3] Q^P denotes the degree of inhomogeneity of the process.

$$\frac{P}{w} = \overline{\sigma}'.\sqrt{R'\Delta h}.Q_p$$

2.4 Precipitation Model

In case of HSLA steels microalloyed with Nb, Ti and V the presence of precipitates in the form of carbides, nitrides and carbonitrides have significant influence in grain growth, recrystallisation behaviour, and precipitation strengthening. When microalloying elements are added in steel in the stoichiometric proportion the precipitation of fine second phase particles retard recrystallisation. During rolling operation strain induced precipitation takes place due to rolling deformation. This makes the recrystallisation sluggish. Precipitation of second phase particles also occurs in ferrite matrix during cooling of strip. This gives strengthening of the matrix.
The HSLA steel derives its strength and toughness through grain refinement. The microalloying elements (Nb, V, Ti) serve specific purposes in the C-Mn steel. While all of them provide precipitation strengthening in steel after hot rolling, vanadium also provides additional benefit of grain refinement after normalising (Table 1). As vanadium carbide is relatively soluble it is added to strengthen steel with higher carbon content. On the other hand, vanadium nitride increases the strength of steels with increased nitrogen content. Vanadium is more soluble in austenite than in ferrite. Hence, during phase transformation vanadium carbides and nitrides precipitate at grain boundaries resulting grain refinement and precipitation strengthening.

Table 1. Principal microalloying compounds and effects.[4]

Element	Precipitation Strengthening after Hot Rolling	Precipitation Strengthening after Normalising	Influences Recrystallization during Hot Rolling	Refines grain size after normalising	Refines grain size during high temperature Austenitizing	Influences Transformation Characteristics after Hot Rolling
V	VN, VC	VC		VN	-	-
Nb	NbCN	-	Nb, NbCN	NbCN	-	Nb
Ti	TiC	-		TiC	TiN	-

Due to little contribution of vanadium on transformation characteristics, hot rolling at different finishing temperatures can be beneficial. Niobium reduces rate of recrystallization of austenite during hot rolling. Controlled rolling is used in hot strip mill for grain refinement. Addition of titanium is effective in controlling austenite grain size at high temperature during reheating. Thus, titanium is used in combination of other microalloying elements for grain refinement during controlled rolling. Amount of titanium addition is well-engineered in order to take full advantage of formation fine titanium nitride precipitates to pin austenite grain growth, and to avoid formation of coarse particles to reduce fracture strength. This also helps during welding operations to avoid coarsening of grains in the heat affected zone (HAZ).

The precipitation model calculates the average particle radius, the volume fraction, the residual amount of solutes in the matrix (and other microstructural

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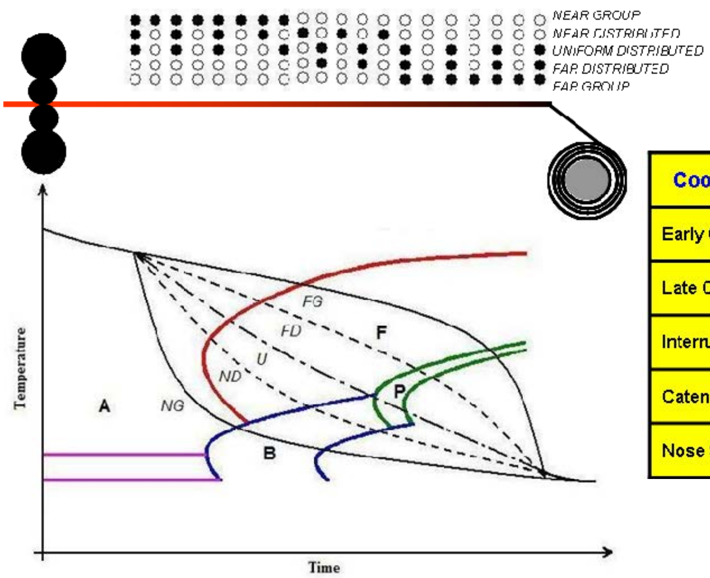
features such as the number of particles per volume unit) of TiC, NbC, VC and AlN. The latter phase does not contribute significantly to the precipitation strengthening but, if nitrogen remains in solid solution, it can determine an indirect effect by interstitial strengthening of the ferrite matrix.

2.5 Phase Transformation Model

In case of low carbon and structural steels the water-cooling on ROT gives the ferrite grains to nucleate along the austenite grain boundaries. With high nucleation rate and low growth rate the final microstructure becomes predominantly fine-grained ferrite, which gives better mechanical properties. But in case of medium and high carbon steel low temperature microstructural constituents include pearlitic and bainitic structure depending on the composition and the cooling rate on the ROT. For HSLA steel, hot rolling produces elongated pancake shaped austenite grains, which upon watercooling produces fine-grained ferrite with better mechanical properties. Ferrite nucleation starts from the deformation bands inside the austenite grains.



Cooling Type	Products
Early Cooling	High Tensile Grade, IF
Late Cooling	HR for CR
Interrupted Cooling	Dual Phase, C-Mn steel, TRIP
Catenary Cooling	Galvanised Product
Nose Suppression	Light Gauge Product

Figure 4. Design of cooling profile and cooling strategy for production of different steel grades

During water-cooling the metallurgical transformations take place within the strip. Transformation from austenite to ferrite is associated with volume change resulting release of heat, which heats up the strip during phase transformation. The final microstructure depends on the rate of cooling. The cooling rate is obtained from the Thermal Model. To produce different products different cooling strategies are adopted. This is accomplished by activating and deactivating the water headers – Near Group (NG), Far Group (FG), Near Distributed (ND), Far Distributed (FD), and Uniformly Distributed (U), as shown in Figure 4. Slow cooling produces Ferrite (F). Lower temperature products, such as Pearlite (P), Bainite (B), and Martensite (M), form with increase in cooling rate. The amount of phases depends on the transformation kinetics and time of transformation. The types of phases can be obtained from the Time-Temperature-Transformation (TTT) diagram.

The kinetics of transformation follows the Avrami type equation.

$$X = 1 - \exp(-kt^n)$$

where k and n are material constants.[5]

2.6 Structure – Property Correlation Model and Artificial Neural Network

The structure-property correlation then relates the property with the respective microstructure. With the knowledge of ferrite grain size, volume fractions of different phases, the size and volume fraction of the precipitates the mechanical properties are estimated. Grain size is related to YS using Hall-Petch relationship. The model also relates property with UTS, EL, and hardness of the material.

Information from the metallurgical models combines with ANN to include the uncertainties involved in the process. The feed-forward network with a hidden layer of neurons in between the input and the output layers has been found to represent accurately the complex relationships between the inputs and the properties. A relationship between input and output can be expressed as a hyperspace whose contour is defined through ‘weights’. Three output neurons, one each for YS, UTS, and EL build the output layer. The network is trained using the Backpropagation (BP) algorithm. The best network topology is then identified by comparing the selection (validation) performance of a set of networks with different configurations. The lowest error between actual mechanical properties and predicted values were obtained. ANN model is useful to carry out the sensitivity analysis.(6) The amount of variation of an output with unit change in input gives the sensitivity of the output, i.e., the mechanical properties. This is useful for the purpose of control of properties of the strip. To improve the accuracy of prediction of mechanical properties different neural networks are used for different steel grades.

3 MODEL VALIDATION & IMPLEMENTATION

After development of all models in the CQE system, they are validated before use. Such validation is done for both conventional Hot Strip Mill (HSM) and Thin Slab Casting and Rolling (TSCR) plant. In 2007, it was validated for conventional HSM in Beta Steel, Indiana, USA.(7) And in 2009, it was validated for the TSCR plant in OMK, Vyksa, Russia.(8) Both the plants were set up/revamped by Danieli.

3.1 Beta Steel, Indiana, USA

Beta steel is located in northwestern Indiana at the southern tip of Lake Michigan. It is located in the region where 60 percent demand for hot band in the United States lie. Beta steel’s major customers are service centres that buy light gauge hot bands to produce pipes. They do not produce strips for automotive applications. It is a scrap based minimill that can produce 1.2 MTPA of hot rolled coil. Its melt shop is equipped with EAF, and can produce 700,000 t steel. Unlike a traditional minimill, that uses thin slab casting, this plant decouples casting and rolling. Therefore, it uses a conventional thick slab caster. It makes slab of 205 mm thick and produces strip of 1.5 – 19 mm. It produces low, medium, and HSLA grades for pipe manufacturers.

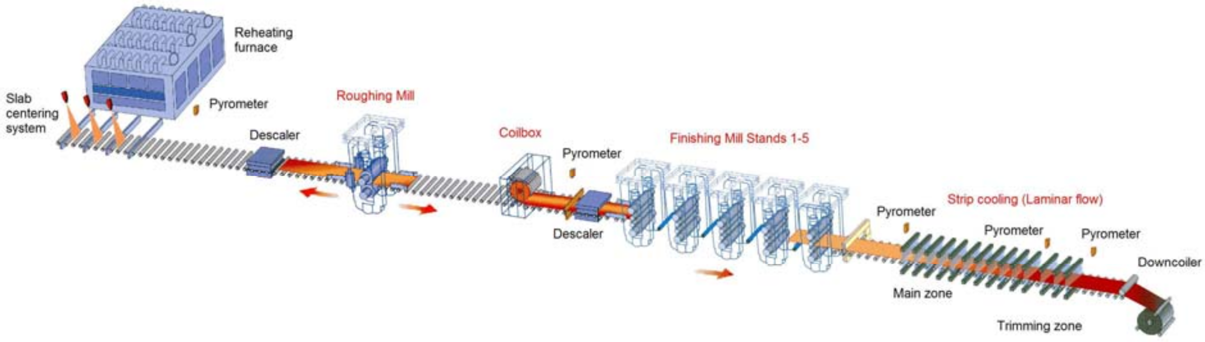


Figure 5. Layout of Beta Steel conventional Hot Strip Mill.

3.2 OMK, Russia

Danieli set up 1.2 MTPA QSP (Quality Strip Production) plant in Thin Slab Casting and Rolling (TSCR) Complex of the United Metallurgical Company (OMK), at Vyksa in Nizhny Novgorod Region, Russia. OMK is one of the leading pipe manufacturers in Russia. The QSP facility uses single strand fTSC caster with Dynamic Soft Reduction to obtain exit slab thickness between 90 - 70 mm starting with 110 – 90 mm slab at the mould exit. The final thickness of strips varies 1.0 – 12.7 mm. The final strip width is 800 – 1,800 mm. It produces low, medium, and microalloyed grades. The plant is equipped with ferritic rolling and TMCP rolling to produce API X70 arctic grade steel operative at - 60 ºC.(8)

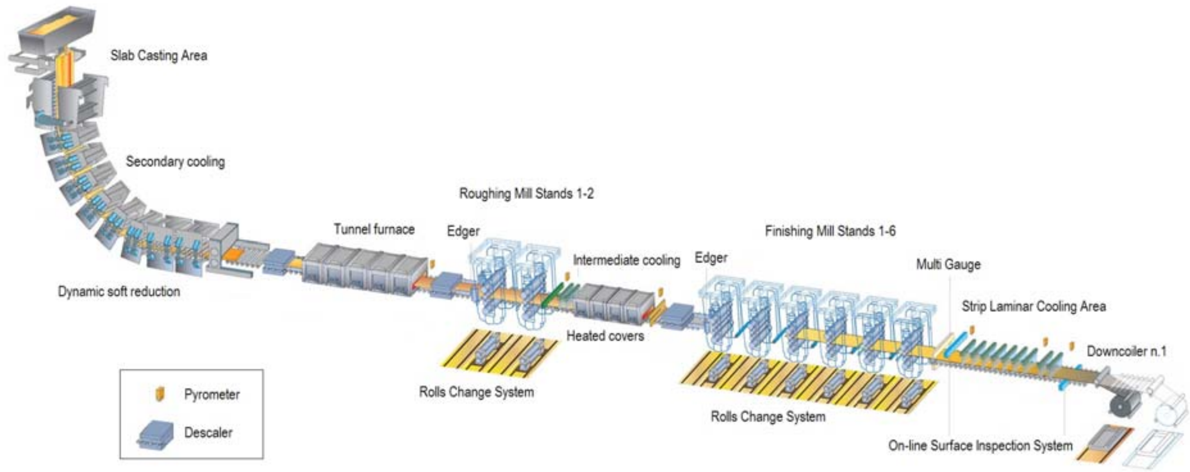


Figure 6. Layout of OMK QSP plant.

Linepipe steel requires low sulphur content for sour service, and high notch toughness for low temperature applications. High strength API grades are produced by addition of microalloying element such as V, Nb, Ti (Figure 7). Increasingly lower carbon, more microalloying elements, and lower sulphur contents are used historically for design of such grades. The Controlled rolling and cooling techniques are used for production of such grades.

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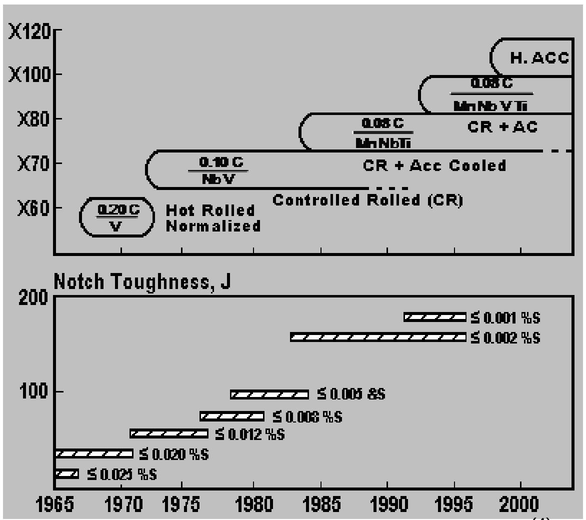

Figure 7. Development of line pipe steels.[4]

4 RESULTS & DISCUSSION

4.1 Validation Results

4.1.1 Beta Steel, Indiana, USA

The results of validation of mathematical models in CQE system are shown through Figures 8 – 12. The validation was done for temperature inside slab, rolling load, torque, and final microstructure. Figures 8a - c demonstrate temperature evolution within the slab of microalloyed steel during roughing, finishing and water-cooling operations. The chemical composition of steel is given in Table 2.

Table 2: Chemical composition (% wt) of steel used for validation

C	Mn	Si	Al	V	Nb	P	S
0.08	0.8	0.04	0.05	0.09	0.008	0.02	0.01

The slab of 205 mm thick is reheated to 1250 ºC, and is then rolled down to a transfer bar of 26.2 mm in 9 successive passes at the reversing rougher. The entry temperature to roughing mill is 1204°C. The evolution of through-thickness temperature as obtained from the thermal model at three different points – centre, surface, and quarter thickness are shown here. The predicted temperatures are compared with the actual temperatures measured from the pyrometers installed in the plant. The locations of the pyrometers are given in Figure 5. These are shown in full circles. The match between the predicted and the actual temperature has been found to be quite satisfactory.

The transfer bar is then reduced from 26.2 mm to 2.6 mm in a sequence of 5 passes in the finishing stand with the exit speed of 7 m/s. The finishing mill entry temperature before secondary descaling is 1025 ºC. The individual reduction per pass is given in Figure 9. The finish rolling temperature (FRT) is 880 °C. As before, the temperature evolution at same three different points at the centre, the quarter thickness, and the surface are shown in Figure 8b. The temperature rise is due to higher reductions at the initial stages of finish rolling. The FRT, as obtained from the model, is compared with that from the pyrometer. As can be seen, the match between the two is quite satisfactory.

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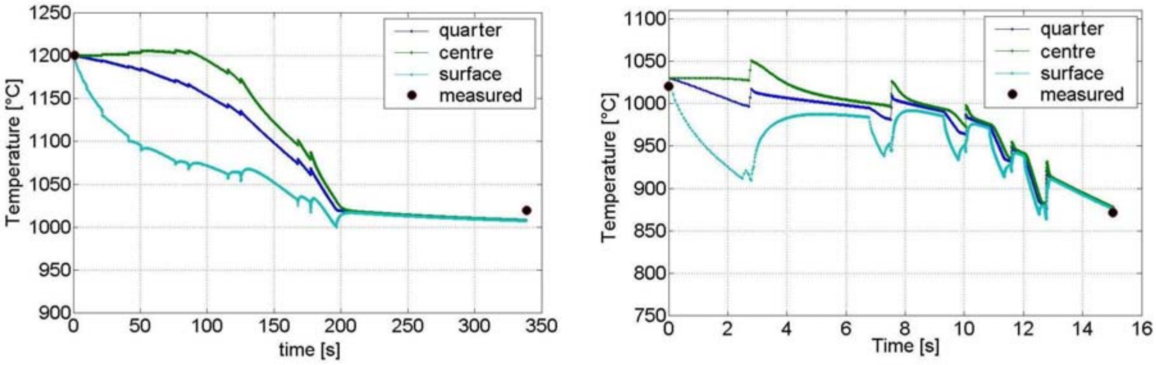

Figure 8a and 8b: Temperature evolution in a slab during rolling at Beta Steel, Indiana, USA

The strip is cooled in a series of laminar water jets on ROT from the finish rolling temperature of 880 ºC to the coiling temperature (CT) of 570 ºC. The temperature validation was done at three points – FRT, intermediate temperature, and CT. The match is found to be very good (Figure 9).

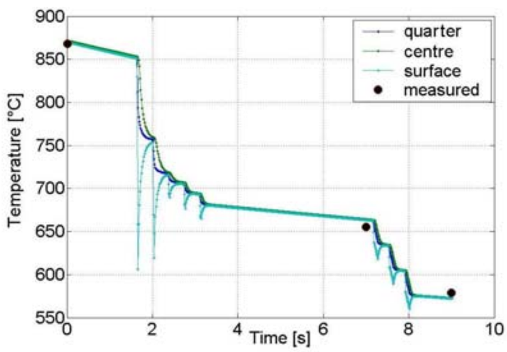

Figure 9: Temperature evolution in a strip during water-cooling on ROT at Beta Steel, Indiana, USA

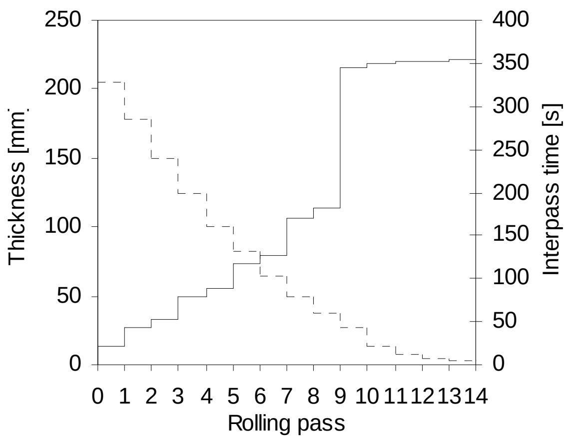

Figure 10: Thickness & inter-pass time.

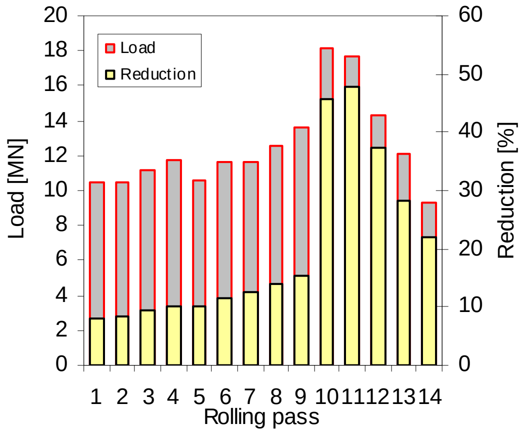

Figure 11: Rolling load & reduction.

Figure 10 shows the reduction sequences and the inter-pass times during rough rolling and finish rolling for rolling from 205 mm thick slab down to 2.6 mm strip in 9 roughing and 5 finishing passes. The rolling reductions and rolling load at individual passes, as obtained from the model are also shown (Figure 11). It shows higher reduction and load at the first finishing stand and lower reductions in the subsequent stands.

Figure 12 shows the difference in recrystallisation kinetics in case of C-Mn and C-Mn-V steel as obtained from the CQE system. While austenite is fully recrystallised in case of C-Mn steel, it is only partially recrystallised in last three finishing passes in case of C-Mn-V steel.

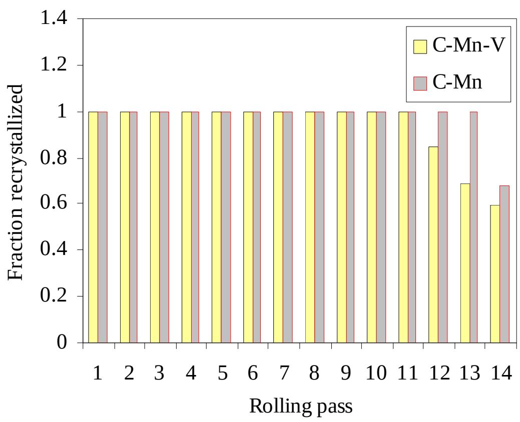

Figure 12: Fraction recrystallised

Figure 13 shows evolution of austenite grain size during roughing and finishing operation for C-Mn and microalloyed steel. The austenite grain size after reheating is about 120 µm. The austenite grains are progressively deformed from 120 µm to 20 µm at the end of finish rolling.

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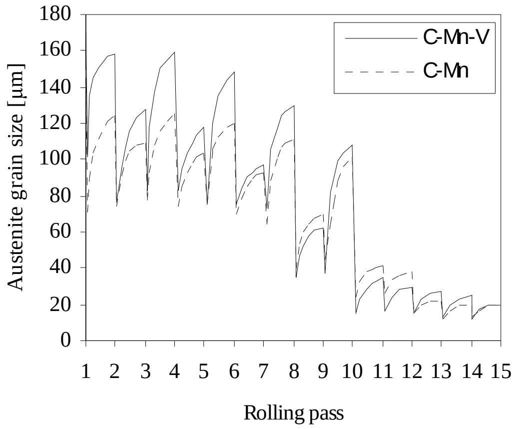

Figure 13: Evolution of austenite grain size.

4.1.2 OMK, Russia

Figures 14 – 18 show the results of implementation in OMK.(9) The model validation was done in terms of ferrite grain size, microstructure, and mechanical properties. The CQE system performance is checked in terms of accuracy and reliability.

Figure 14: Variation of Mechanical Properties over strip length.

The prediction of properties over the length of a coil is shown in Figure 14. The variations of YS, UTS, EL and HV are shown for a specific coil. The ordinate shows the magnitudes of properties in absolute scale, and the abscissa shows the strip length in meter. The drop in strength at the extremes shows some un-cooled portion of the strip.

Figure 15 shows the ferrite grain size and volume fractions of different microstructural constituents – ferrite, pearlite, bainite and martensite for a given coil. It also estimates the mechanical property values at different points over the strip. For convenience, the statistical estimates of properties at three points are shown. The property values are estimated in real time.

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After implementation and commissioning the system output is verified to estimate the prediction accuracy. First, the ferrite grain size of the strip is tested. To do so, a set of 70 coils are chosen which covers low and medium carbon steels with high manganese and also microalloyed grades. The samples from the coils are cut for metallographic examination. From the optical micrographs the grain size is estimated. At the same time, the process history data of these 70 coils are given in the CQE system for prediction of ferrite grain size.

DANIELI AUTOMATION — **Coil Quality Estimator Report** 101112302 — OMK STEEL UNITED METALLURGICAL COMPANY

OUTPUT COIL DATA					
Heat ID	1011123	Thickness [mm]	8.78	Customer	CUST1
Slab ID	10112302	Width [mm]	1570	Production Start Date	05/07/2010 14.41.54
Chemical Code	22GU-1	Diameter [mm]	700.3	Production Stop Date	05/07/2010 14.45.41
Steel Grade	22GU-1	Weight [kg]	-1		

MICROSTRUCTURE PROPERTIES	HEAD		BODY		TAIL	
	Aver.	St. Dev.	Aver.	St. Dev.	Aver.	St. Dev.
Ferrite [%]	96.1	1.2	96.1	1.1	96.1	1.2
Perlite [%]	3.9	1.1	3.9	1.2	3.9	1.1
Bainite [%]	0	0	0	0	0	0
Martensite [%]	0	0	0	0	0	0
Grain Size [um]	4.2	0.4	4.3	0.3	4.3	0.6

ROT DATA	HEAD		BODY		TAIL	
	Aver.	St. Dev.	Aver.	St. Dev.	Aver.	St. Dev.
Speed [m/s]	2.7	0.8	2.7	0.8	2.7	0.8
F6 Exit Temp. [C]	853	11.1	853	11.1	853	11.1
Interm. Temp. [C]	615	15.1	615	10.8	615	18.3
Coiling Temp. 1 [C]	499	6.3	499	6.8	499	6.3
Coiling Temp. 2 [C]	505	6.8	505	6.3	505	6.3

MECHANICAL PROPERTIES	HEAD				BODY				TAIL			
	Aver.	Min.	Max.	St. Dev.	Aver.	Min.	Max.	St. Dev.	Aver.	Min.	Max.	St. Dev.
YS [MPa]	388.7	384.3	393	1.2	388.3	383.1	395.4	2.3	387.5	385	394	1.5
UTS [MPa]	588	584	595	1.4	589	583.2	593.4	1.2	589	585.8	594.5	1.5
EL [%]	22.3	22.3	22.3	0	22.3	22.3	22.3	0	22.3	22.3	22.3	0
HV	161.2	160.6	163.2	1.1	161.1	159.9	164	1.3	161.2	160.4	163.4	1.2

Figure 15: Microstructure and Mechanical Properties at different position on strip.

The measured grain size is then compared with the grain size predicted from CQE for each coil. This is shown in Figure 16. A good match is obtained between the actual and the predicted values. It is to be noted that the figure covers a wide range of ferrite grain size from 4 – 14 µm.

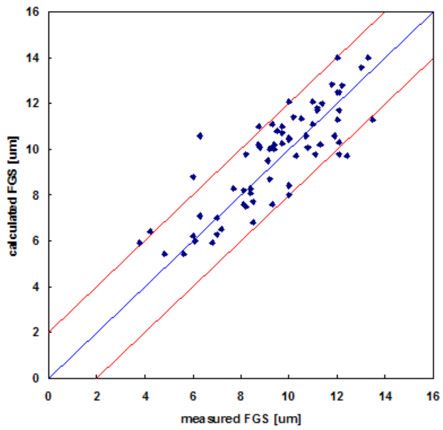

Figure 16: Comparison of Measured and Predicted Ferrite Grain Size.

4.2 Performance Results

For testing accuracy and reliability of prediction of mechanical properties of CQE system 3200 coils are chosen at random. This covers all the existing grades. Both the process related data and mechanical testing data are collected. The actual mechanical testing data for YS, UTS, EL, and HV are collected from the Testing Laboratory of the OMK. The CQE predicted values are then compared with the measured data.

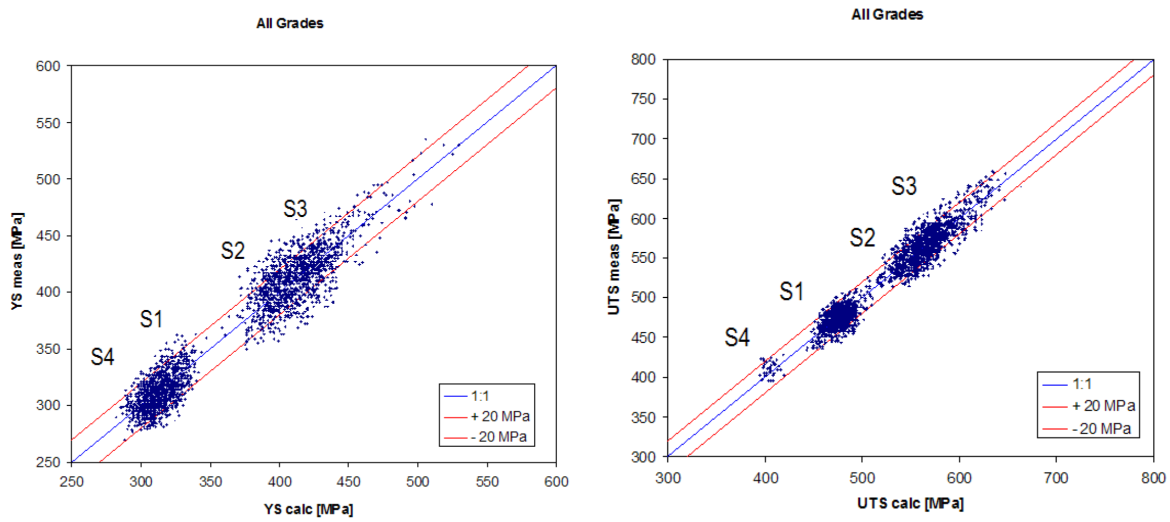

Figure 17: Comparison between measured vs. predicted (a) YS, and (b) UTS

Figure 17(a) shows the comparison of YS between the actual and the CQE predicted values of all data. A good match is obtained with majority of the points within the limits of ± 20 MPa. Similarly, Figure 17(b) shows the comparison of UTS between the measured and the CQE estimated ones. Again, a good match is obtained with large number of samples falling within the red lines. Compared with YS the scatter for UTS is less.

The accuracy of prediction is obtained as ± 16 MPa for YS, ± 15 MPa for UTS, and ± 4.6 percent for EL. These results are at the reliability level of 68.2 percent.

4.3 Sensitivity Analysis

It is interesting to note that the majority of YS data are divided into two main clusters – one in 280-340 MPa range and another in 375-450 MPa range. On the other hand, the majority of UTS data are in three clusters – around 450 MPa range, between 450-500 MPa range, and 525-600 MPa range. These are discussed below with reference to the sensitivity of the CQE model.

In order to understand the clusters better 4 samples of different steel grades are chosen from the two YS clusters. These are chosen from approximately the upper and the lower end of each of the above clusters. This covers a wide range of strengths so far as different steel grades are concerned. The locations of the samples are shown in Figures 17(a) and (b). The chemical compositions and process parameters are given in Table 3.

For the purpose of comparison and sensitivity analysis the first sample (S1) is considered as the base sample. S1 is low carbon structural steel processed with late cooling. The second sample (S2) has higher manganese and lower CT. Sample 3 (S3) is of low carbon microalloyed grade with the microalloying elements of Ti, Nb, and V. It is processed with distributed cooling (D). Sample 4 (S4) is of lower carbon and manganese content with little microalloying elements.

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Table 3: Sensitivity Analysis of CQE

SAMPLE	C %	Mn %	Si %	P %	S %	Al %	Ti %	Nb %	V %	FRT ºC	CT ºC	COOLING STRATEGY
S1	0.2	0.5	0.22	0.015	0.012	0.03	-	-	-	890	690	F
S2	0.19	1.3	0.22	0.015	0.012	0.03	0.02	-	-	870	560	U
S3	0.09	0.6	0.6	0.015	0.001	0.04	0.03	0.04	0.08	860	550	U
S4	0.16	0.35	0.05	0.015	0.001		0.002	<0.01	<0.01	900	570	F

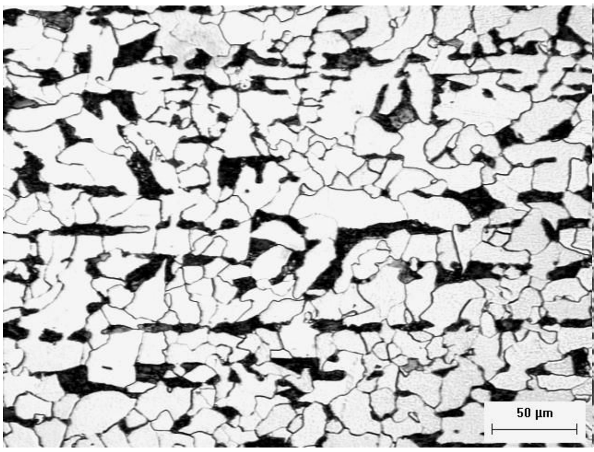
***Note :** Cooling Strategy: FG – Far Group Cooling; U – Uniformly Distributed Cooling*[1]

These samples are then etched and the prepared for optical microscopy. Figures 18a - d show the optical micrographs of the four samples. Figure 17a corresponds to sample 1. It shows ferritic-pearlitic structure with some deformed grains. Banding is not fully developed. A higher CT results in lower YS.

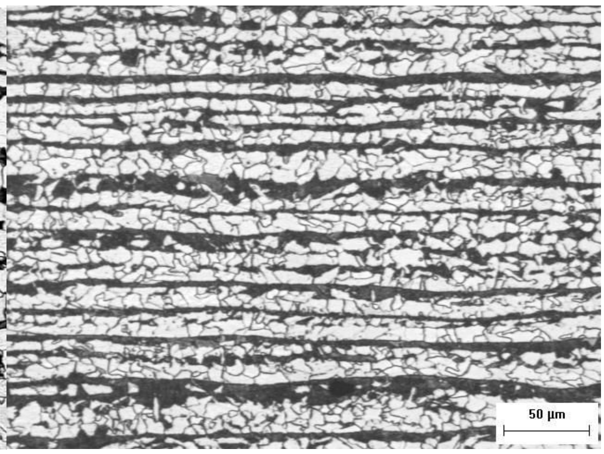
Figure 18b shows the optical micrograph of the sample 2 (S2). It is ferritic-pearlitic steel with fully developed banded structure. Ferrite grain size is smaller than the earlier case. Smaller ferrite grain size causes the YS value higher than S1.

Figure 18c corresponds to the sample 3. The microstructure is different from the first two. The ferrite grain size is a mixture of mostly small and partly large elongated grains. Due to smaller carbon content there is little pearlite. The material strength of this microalloyed grade is mostly due to smaller ferrite grains.

Figure 18d corresponds to the micrograph of the last sample (S4). The structure is predominantly polygonal ferrite. Larger grain size compared to all other previous samples makes the steel the lowest strength.



(a)



(b)

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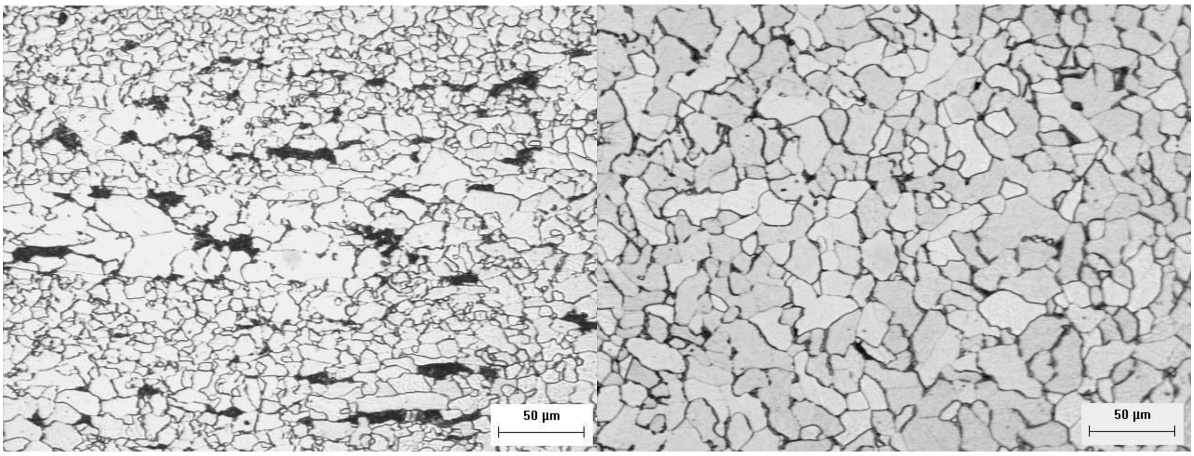

(c) (d)

Figure 18: Microstructure of: (a) Sample 1 (S1), (b) Sample 2 (S2), (c) Sample 3 (S3), (d) Sample 4 (S4).

5 BENEFITS

The CQE system has many advantages. The test certificate is ready as soon as the coil is rolled. Hence, it is useful for automatic product certification, and acceptance testing. Reduction in sampling and testing cost due to real-time product assessment, reduction of inventory holding cost, quicker delivery schedule, and better customer management are the key benefits. It is useful for internal certification of products also. Secondly, the customer uses for new product development. For demand of a new product in market, the system can design the steel chemistry and define the appropriate process window to roll it in mill. Thirdly, it also suggests grade rationalization, and thereby, reduces the cost of expensive ferroalloys in steelmaking stage. Fourthly, it is useful for process optimization. It determines the minimum amount of resources (fuel. electricity, water, and compressed air) required to produce any particular grade of steel. Finally, the system is capable to perform the sensitivity analysis to assess the impact of chemistry and process parameters on final properties. These benefits are enumerated in Table 4.

Table 4: Benefits of DANIELI CQE System

Benefits	Type
Product certification	▪ Automatic certification and generation of test certificate ▪ Product acceptance testing
Product development	▪ Rationalization of steel grades ▪ New product development
Quality assurance	▪ Ensures desired quality
Process optimization	▪ Minimise resources such as fuel, electricity, water, etc. ▪ Reduce process cost
Customer complaint handling	▪ Customer complaint handling

6 CONCLUSION

The conventional mechanical testing measures properties at the end of the coil. Properties inside the coil remain grossly unknown. CQE provides this information; it provides such information when it is most needed – during processing, and not any time afterwards, as is practised today. Hence, the corrective action can be taken by the plant operators during production stage itself. The system was validated/ and implemented in Beta Steel, USA, and OMK, Russia. The plants are benefitted through implementation of such innovative technology. Successful development, validation and implementation of CQE in steel plants show how fundamental metallurgical research is applied in real process to provide with superior quality of HR coil at reduced cost and better sustainability.

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