INNOVATIVE SOLUTION TO PRODUCE HIGH QUALITY LONGS THROUGH INTEGRATED CONTROL BETWEEN CASTING AND ROLLING[1]

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Abstract

Quality of steel mill products is mainly characterized by mechanical property, dimensional tolerance, and surface appearance. Thus, uniform mechanical property, desired tolerance, and required surface finish are essential to produce high end products. In case of mechanical property, much of this has already been achieved through sophisticated modelling and control for individual processes of casting and rolling, and also through better operational practice. However, to produce good quality rebars and wire rods, a good quality billet, free from internal defects and cracks, is a prerequisite. Danieli's philosophy towards production of high quality long products involves through-process modelling and control of casting and rolling processes. The casting automation solutions such as Liquid Pool Control System, Dynamic Secondary Cooling, and Dynamic Soft Reduction provide the billet with internal soundness - free from internal defects, segregation. This also gives favourable grain structure through improved solidification. On the other hand, rolling solution such as system for Advanced Quenched and Tempered Bar (QTB Plus) ensures desired mechanical property and its uniformity over entire length of the product in real-time processing in the rolling mill. Thus, an integrated modelling and control between steel casting and rolling is important to produce high quality long products. The integrated solution is implemented in CMC Steel, Arizona, and some in part in European Mills.

Key words: Danieli; High quality production; Integrated solutions; Casting; Hot rolling.

SOLUÇÃO INOVADORA PARA PRODUZIR PRODUTOS LONGOS DE ALTA QUALIDADE ATRAVÉS DE CONTROLE INTEGRADOS ENTRE LINGOTAMENTO E LAMINAÇÃO

Resumo

A qualidade dos produtos siderúrgicos é caracterizada principalmente por propriedades mecânicas, tolerância dimensional e acabamento superficial. Assim, propriedade mecânica uniforme, tolerância de acabamento superficial são desejados e requeridos para produzir produtos finais de alta qualidade. No caso das propriedades mecânicas, muito já se foi alcançado através de modelagem sofisticada e controle dos processos individuais de lingotamento e laminação, e também através de uma melhor prática operacional. No entanto, para uma produção com boa qualidade de vergalhões e fio-máquina, um tarugo de boa qualidade, isento de defeitos internos e rachaduras, é um pré-requisito. A filosofia da Danieli em relação à produção de produtos longos de alta qualidade, envolve o processo de modelagem, controle de lingotamento e laminação. As soluções de automação para lingotamento, tais como *Liquid Pool Control System*, *Dynamic Secondary Cooling* e *Dynamic Soft Reduction* fornecem tarugos com solidez interna - livre de defeitos internos e segregação. Isso também produz uma estrutura de grãos favorável, através de uma melhor solidificação. Por outro lado, sistemas para laminação , como o *Advanced Quenched* e *Tempered Bar* (QTB Plus), garante em tempo real a propriedade mecânica desejada e sua uniformidade ao longo de todo o comprimento do produto, durante o processo de laminação. Portanto, uma integração entre modelos e controles, no lingotamento e na laminação é fundamental para produzir produtos de alta qualidade. Este tipo de solução integrada é encontrado no Arizona na CMC Steel, e em parte, em alguns laminadores na Europa.

Palavras-chave: Danieli; Produção de alta qualidade; Soluções integrada; Lingotamento; Laminação a quente.

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1 INTRODUCTION

The sustainable development in the steel industry is driven by technologies that not only help to reduce production cost, but also enable to produce superior quality product with minimum downgrading, reduced yield-loss with economic use of raw materials and energy. To address these issues Danieli proposes the concept of "Through-Process Control" between casting and rolling processes. Quality of long products is mainly characterized by mechanical property, dimensional tolerance, and surface appearance (Figure 1). In case of mechanical property, while much of this can be achieved through sophisticated process control and good operational practice, needless to say that a good quality billet/bloom is an imperative for this. Thus, cleanliness and internal soundness of billets are some of the prerequisites. The automation solutions for casting process such as Liquid Pool Control (LPC) System, and Dynamic Soft Reduction (DSR) provide billets with good surface quality and internal soundness. This can be assessed in Real-time through the billet QUality Assessment System (Quart). Hence, such billets are free from surface and internal cracks, non-metallic inclusions, internal stress, segregation, and give favourable grain structure through improved solidification. On the other hand, automation solution in hot rolling such as Advanced Quenched and Tempered Bar (QTB Plus) System ensures desired mechanical property and its uniformity over entire length of a bar in real-time processing in the rolling mill.(1,2) An integrated solution, therefore, is necessary. Thus, the "Through-Process Control" of casting and rolling processes give future solutions to produce high quality bars/wire rods/sections. This paper describes the concept of Through-Process Control, and how this can be applied in unison to produce superior quality long products.

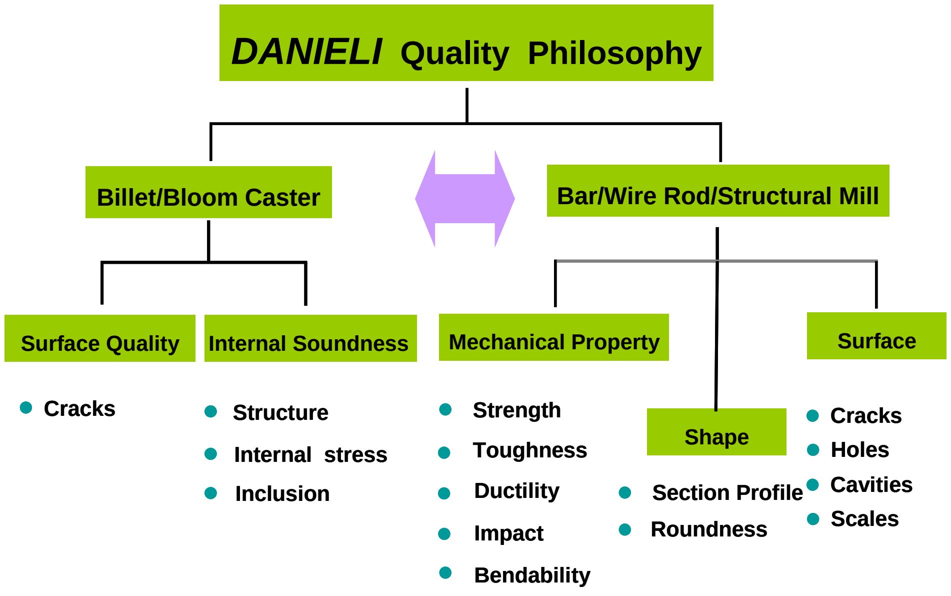
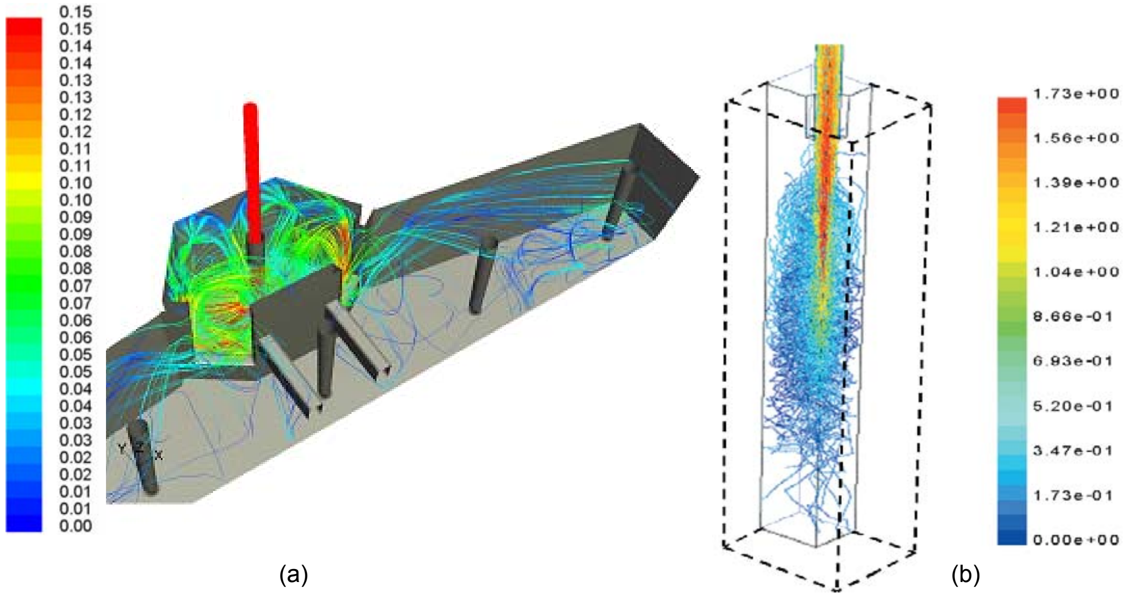


Figure 1. Through-Process control philosophy between casting and rolling.

2 QUALITY SOLUTIONS FOR CONTINUOUS CASTING

2.1 Fluid Flow Inside Mould

Steel cleanliness requires control on chemistry and desired fluid flow in mould during continuous casting operation. With high flow speeds there is increased tendency of entrapment of mould powder and hence, formation of non-metallic inclusions in steel. Figure 2a shows distribution of liquid metal flow through the tundish. The velocity profile of inclusions within the mould is important as it provides the likelihood of inclusion entrapment (Figure 2b).



(a) (b)

Figure 2. (a) Flow distribution through the tundish; and (b) Velocity distribution within the Conticaster mould.

2.2 EMS (Electromagnetic Stirrer)

Nearly all quality billet or bloom casters in the world today have adopted electromagnetic stirring. This improves surface or sub-surface cleanliness, segregation, porosity, inter-columnar cracks, grain refinement, and shell-thickness uniformity. It enhances machine throughput and reduces breakout frequency. The stirrers are installed either around the mould or along the strand. M-EMS is meant for mould stirring (Figure 3a). S-EMS is used for stirring high in the strand and F-EMS is applied for stirring in the final solidification zone. The stirrers can be used in any combination depending on the steel grade that is cast. The two mostly used configurations are 3-phase electrical current with M-EMS for low and medium carbon grades, and M + F-EMS for high carbon and high alloy grades. The S-EMS is used in special cases of large sections in combination with M-EMS. The M-EMS provides all the advantages mentioned above. Moreover, it increases equiaxed zone through earlier dissipation of steel superheat compared to S-EMS (Figure 3b). The transition from columnar to equiaxed structure is driven by the number of solidification nuclei through appropriate cooling and elimination of superheat. These two effects are more predominant in the mould than anywhere below it. As a result of increased equiaxed zone centerline segregation and porosity are better in M-EMS compared to S-EMS. Figure 3c shows improved surface conditions for billets with stirring facilities.

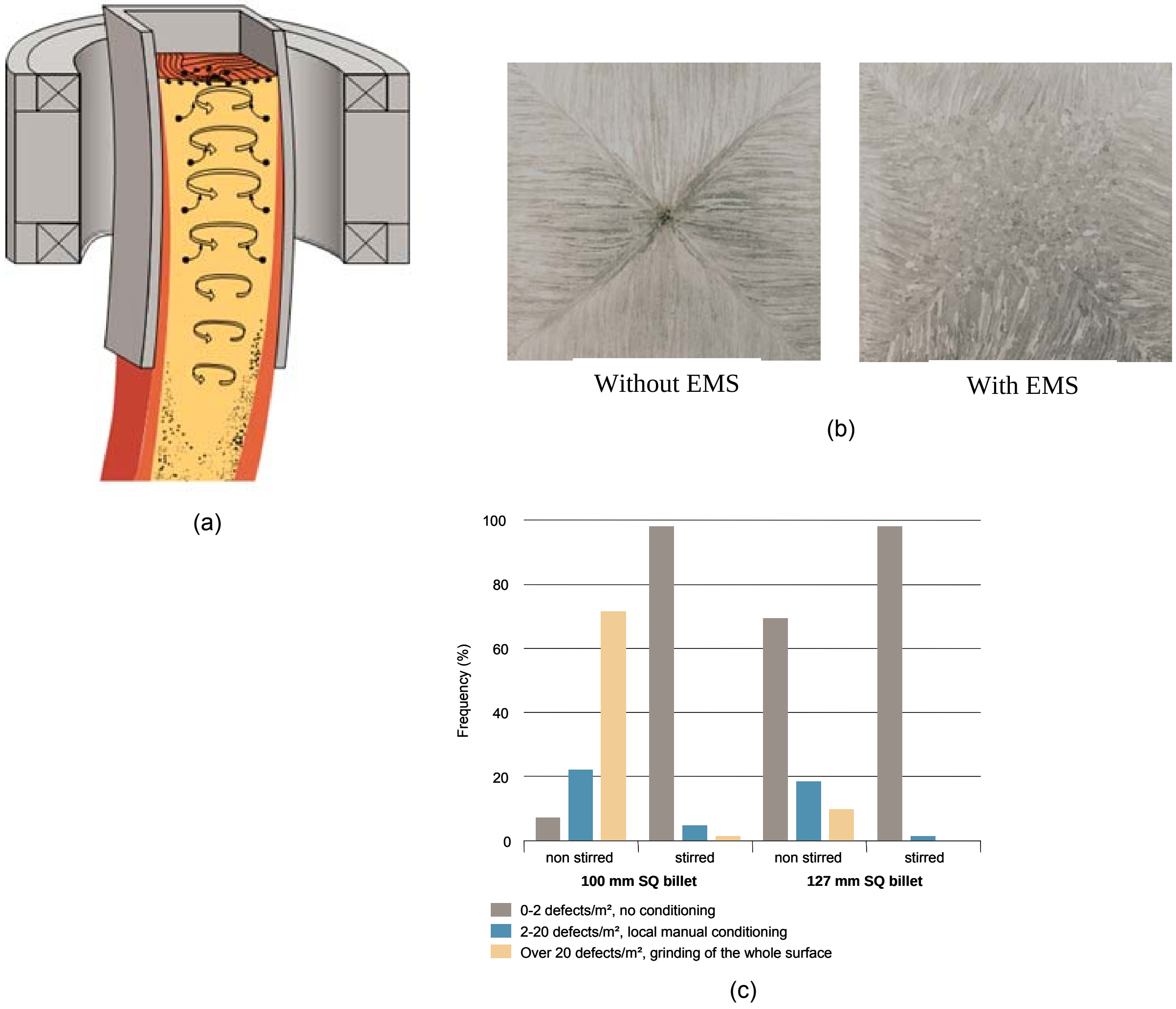
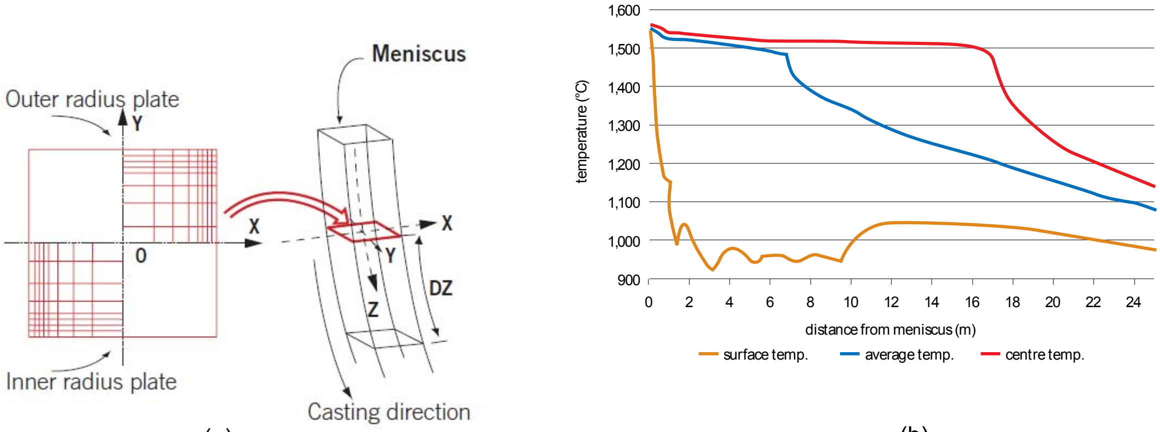


Figure 3. (a) M-EMS controlling fluid flow inside mould; (b) Grain structure refinement with M-EMS; and (c) Comparison of defects in billets produced with and without M-EMS

2.3 LPC (Liquid Pool Control)

The Liquid Pool Control (LPC) system is based on on-line mathematical model that calculates the billet temperature depending on steel grade, tundish temperature, flow inside mould, water flow rate and casting speed. It is a two-dimensional finite difference model that solves Fourier heat conduction equation. Figure 4a shows the computational grid used for analysis. The output is the temperature profile along the cast billet right from the meniscus down to the cutting torch (Figure 4b). The system shows the solidification curves and shell thickness for optimal control of cooling water. The inflection point on the centre temperature profile shows the end of liquid zone inside billet. For any given steel grade and casting speed, the purpose of cooling water control is to maintain a target temperature profile along the strand. The billet temperature profile calculated from LPC system is sent to the PLC. This is then compared with the target temperature. The spray water flow rate is controlled to minimize the difference. The water flow rate is changed dynamically (Dynamic Secondary Cooling, DSC) as the casting speed changes. This is done using feed-forward control.(3)



(a) (b)

Figure 4. (a) Computational Grid used in thermal model for a section of cast billet; and (b)Temperature distribution inside cast billet.

The HMI also shows other important parameters such as current mould level, oscillation type, frequency, magnitude etc. The M-EMS parameters such as current drawn during operation are also displayed.

2.4 DSR (Dynamic Soft Reduction)

The purpose of soft reduction is strictly metallurgical, and is related to internal quality of the billet. Soft reduction is the increased reduction in roll gap, above the normal thermal contraction rate, to provide a gradual “squeezing” of the strand in order to compress the centerline of the billet at the final point of solidification and thus improve the final billet internal quality. The external mechanical pressure applied to the billet during soft reduction prevents the formation of centerline porosity, segregations and chemical discontinuities caused due to solidification bridges and thermal shrinkages. The mechanical pressure breaks down solidification bridges. It is applied in the mushy zone, and thereby prevents the suction of solute rich material into the centre of the billet at the final point of solidification. This promotes movement of liquid steel into the mushy region that compensates for thermal shrinkages, and thereby creates billet with pure core.

Figure 5 shows the functional description of Dynamic Soft Reduction. Unlike static soft reduction where the caster is set at a predefined casting condition, in dynamic soft reduction the roll gap of each segment is adjusted dynamically depending on casting conditions (casting speed, superheat, steel grade, and cooling pattern)**.** The DSR selects the cylinder positions based on calculated positions of liquid and mushy zones inside the strand.

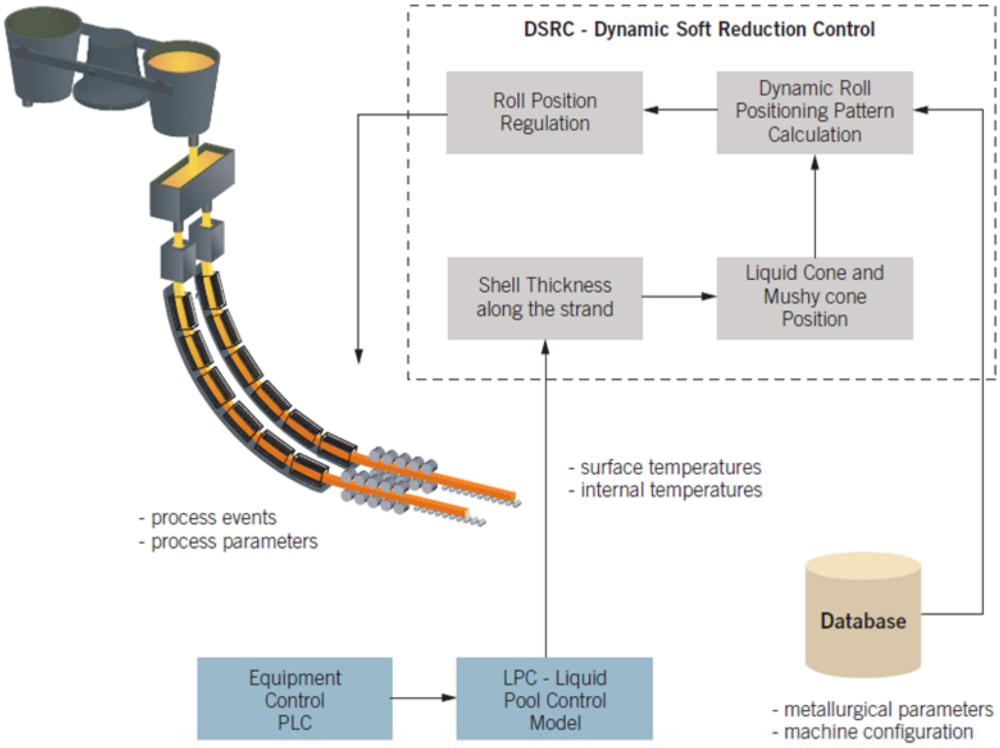


Figure 5. Dynamic Soft Reduction (DSR) control system.

As already explained, the principal system that governs DSR is the LPC system, which predicts the "movement of the mushy zone" along the strand as the casting speed changes. Based on casting conditions, the LPC system predicts mushy-to-liquid ratio of the billet for each transverse cross-section (Figure 6). The soft reduction cylinders are adjusted according to a PLC algorithm that selects the optimal reduction pattern.

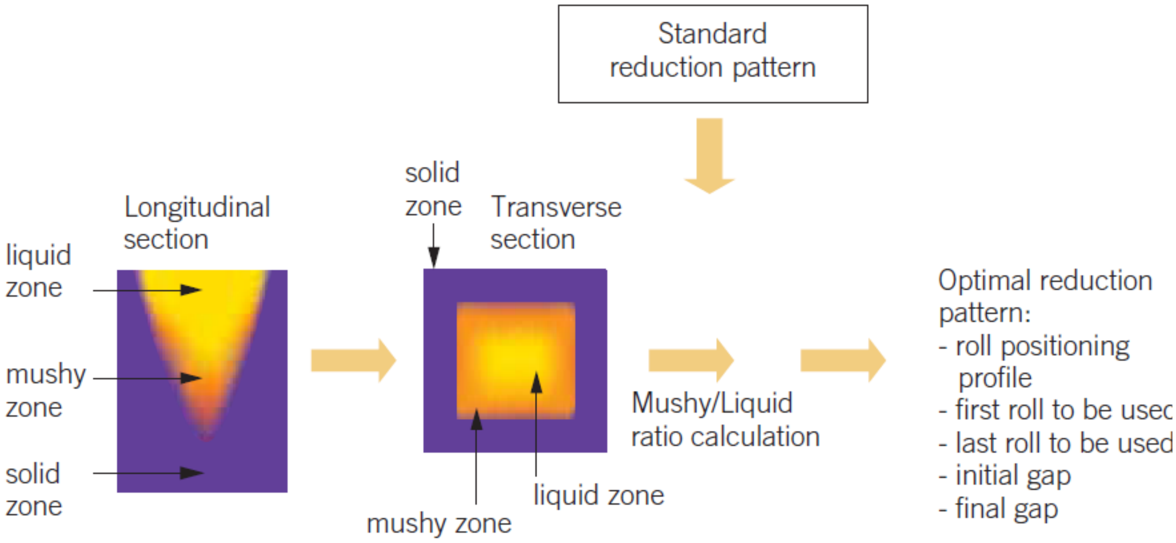


Figure 6. Dynamic soft reduction control strategy.

(a) (b)

Figure 7. Comparison of internal quality of C45 billet of section 350 × 320 mm (a) without DSR; and (b) with DSR.

Figure 7 shows the relationship between internal quality of billet and soft core reduction practice. In case of static reduction practice only optimized casting speed gives good internal structure. Casting speed away from the optimal gives either cracks or centerline segregation/porosity (Figure 7a). On the other hand, dynamic soft core reduction always provides internal structure free from defects (Figure 7b).

2.5 Quart (Quality Assessment in Real Time)

Quart is a computer based cast product quality assessment system. It provides the operators with real time assessment of billet quality and immediate warnings of process variables resulting poor cast quality. Figure 8 gives an overview of the system. The system works in two main steps – Quality Rules Evaluation, and Quality Level Assignment.

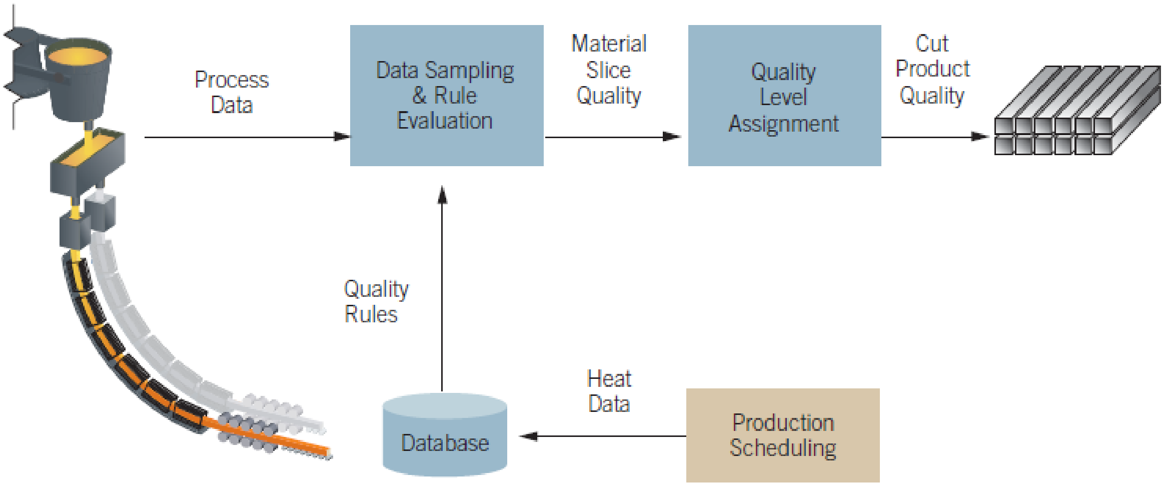
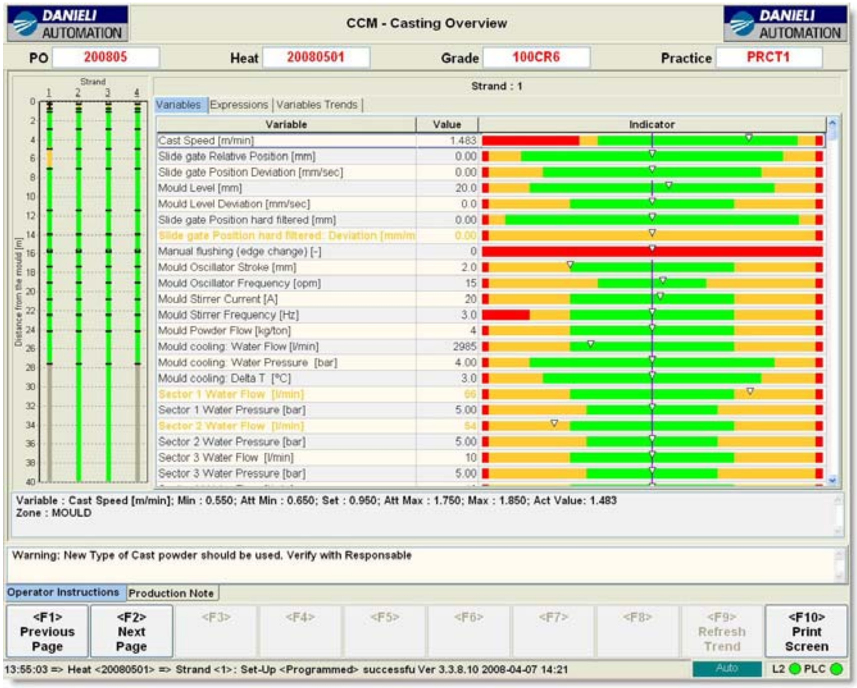


Figure 8. QUART^{TM} control diagram.

2.6 Quality Rules Evaluation

In this step, the relevant process variables are captured through Level I PLCs. The real-time sampling rate depends on casting speed (e.g., speed 3 mpm, resolution 50 mm, sampling rate = 1 s). The Quality Rules that are defined for a heat in Quart are checked for all emerging product slices. Hence, quality is assessed through predefined rules. Such rules can be simple or complex, The Quality Index (QI) is then estimated against all emerging product slices. These QIs can be customized (Figure 9).



PO 200805 Heat 20080501 Grade 100CR6 Practice PRCT1

Variable	Value
Cast Speed [m/min]	1.483
Slide gate Relative Position [mm]	0.00
Slide gate Position Deviation [mm/sec]	0.00
Mould Level [mm]	20.0
Mould Level Deviation [mm/sec]	0.0
Slide gate Position hard filtered [mm]	0.00
Slide gate Position hard filtered: Deviation [mm/m	0.00
Manual flushing (edge change) [-]	0
Mould Oscillator Stroke [mm]	2.0
Mould Oscillator Frequency [opm]	15
Mould Stirrer Current [A]	20
Mould Stirrer Frequency [Hz]	3.0
Mould Powder Flow [kg/ton]	4
Mould cooling: Water Flow [l/min]	2985
Mould cooling: Water Pressure [bar]	4.00
Mould cooling: Delta T [°C]	3.0
Sector 1 Water Flow [l/min]	66
Sector 1 Water Pressure [bar]	5.00
Sector 2 Water Flow [l/min]	54
Sector 2 Water Pressure [bar]	5.00
Sector 3 Water Flow [l/min]	10
Sector 3 Water Pressure [bar]	5.00

Variable : Cast Speed [m/min]; Min : 0.550; Att Min : 0.650; Set : 0.950; Att Max : 1.750; Max : 1.850; Act Value: 1.483
Zone : MOULD

Warning: New Type of Cast powder should be used. Verify with Responsable

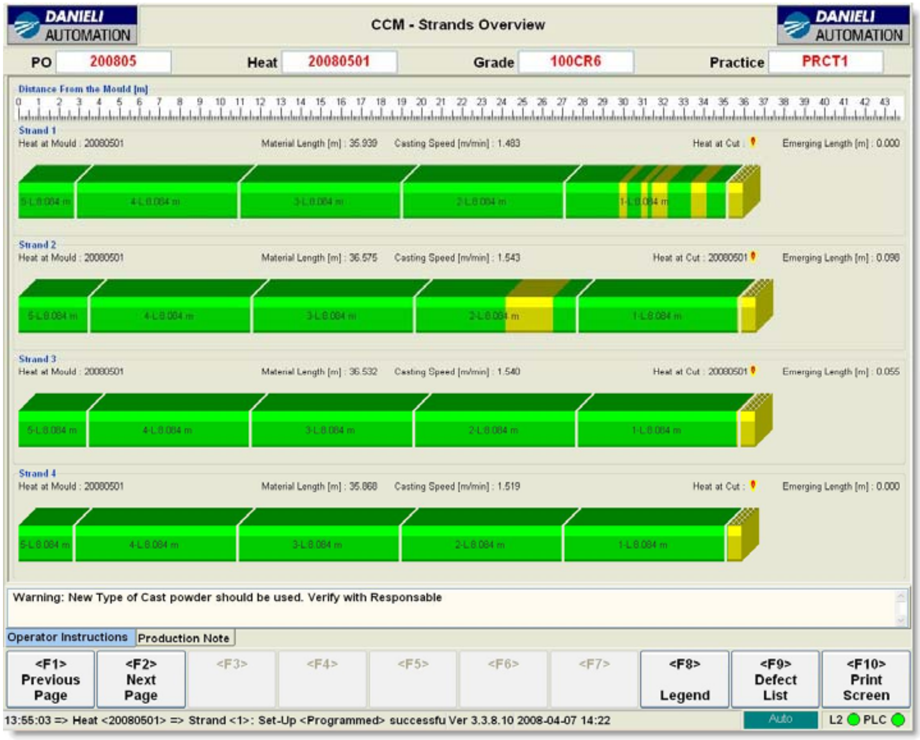
13:55:03 => Heat <20080501> => Strand <1>: Set-Up <Programmed> successfu Ver 3.3.8.10 2008-04-07 14:21

Figure 9. Assessment of process variables along billet length for quality mapping in Nucor Steel Rolling Mills, at Memphis, Tennessee, USA.

2.7 Quality Level Assignment

When the product is cut the Quart summarizes all the slice quality indexes into a Product Quality Index (QID). The QID is then compared with qualification ranges required by the product schedule and the product Quality Level (QL) is finally assigned (Figure 10). The QL is passed into automation units that control downstream processes, together with all the other billet data. This is then used to direct the handling of product in the plant.

With the Quart system billets can be processed more efficiently and accurately for any direct hot-charging and cold-charging processes including conditioning. Accurate defect severity assignment would avoid unnecessary inspection, hot/cold scarfing or grinding operations. On the other way, defects that could have otherwise been overlooked would be properly identified. It would also advise appropriate billet conditioning for suitable end-use.



CCM - Strands Overview

PO 200805 Heat 20080501 Grade 100CR6 Practice PRCT1

Strand 1
Heat at Mould : 20080501 Material Length [m] : 35.939 Casting Speed [m/min] : 1.483 Heat at Cut : Emerging Length [m] : 0.000

Strand 2
Heat at Mould : 20080501 Material Length [m] : 36.575 Casting Speed [m/min] : 1.543 Heat at Cut : 20080501 Emerging Length [m] : 0.098

Strand 3
Heat at Mould : 20080501 Material Length [m] : 36.532 Casting Speed [m/min] : 1.540 Heat at Cut : 20080501 Emerging Length [m] : 0.055

Strand 4
Heat at Mould : 20080501 Material Length [m] : 35.868 Casting Speed [m/min] : 1.519 Heat at Cut : Emerging Length [m] : 0.000

Warning: New Type of Cast powder should be used. Verify with Responsable

13:55:03 => Heat <20080501> => Strand <1>: Set-Up <Programmed> successfu Ver 3.3.8.10 2008-04-07 14:22

Figure 10. Quart^{TM} implementation in Nucor Steel Rolling Mills, at Memphis, Tennessee, USA showing final quality assessment of a billet.

3 QUALITY SOLUTIONS FOR HOT ROLLING

Billets of good surface and internal quality are required to process in the Rebar/Wire Rod Mill and Medium Light Structural Mill to produce long products. Billets free from surface cracks, subsurface inclusions, segregation, and internal porosity increases the possibility to be directly charged into the reheat furnace without further inspection. Quality information from Quart for different segments of the cast billet can be made available to mill automation system for proper reheating and descaling need. Quality of long product can then be controlled using Danieli Quality Estimator system. In this paper the quality solution only for rebar is discussed as an example.

3.1 QTB Plus (Advanced Quenched & Tempered Bar) System

Danieli's Advanced Quenched & Tempered Bar *(Danieli-QTB Plus)* system is a real-time Level II system meant for prediction of mechanical properties of the hot rolled rebars during actual processing in Rebar Mill. The Yield Strength (YS), Tensile Strength (TS) and Hardness (HV) are estimated. QTB Plus simulates the thermo-mechanical processing behaviour of steel and gives the final microstructure which is then related to properties. Properties estimated purely from the final microstructure give a fair overall assessment of properties.(4) But the bar-to-bar variations within a grade are due to uncertainties of the processes. These are tackled using statistical and soft computing based techniques, such as Artificial Neural Network (ANN).(5) The QTB Plus system is available for low carbon grades.

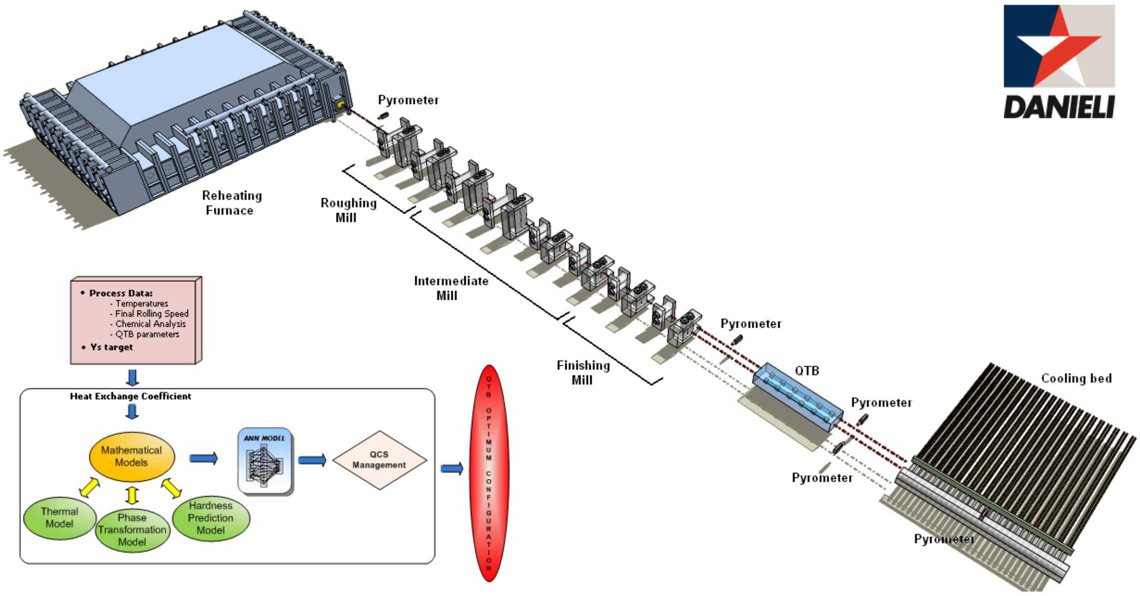


Figure 11. Overview of QTB PLUS System at Siderurgica Sevillana, Spain.

Figure 11 shows the plant layout and an overview of QTB Plus system operating in the Bar Mill of Siderurgica Sevillana, Spain.(6,7) The Thermal Model simulates the temperature evolution of the bar using a one-dimensional finite difference heat transfer model. It provides with estimation of the cooling rate required for phase transformation upon water-cooling in water box. The Phase Transformation Model predicts the volume fraction of ferrite, pearlite, bainite, martensite and tempered martensite. The Hardness Prediction Model estimates hardness from the volume fraction of different phases. It provides HV10 as output. The pieces of information from the metallurgical models are supplemented by the Artificial Neural Network (ANN) model in order to take into account the uncertainties involved in the actual processing in the plant. The model provides YS and UTS as output. A detailed description of the models can be obtained elsewhere.(8,9) Figure 12 shows the temperature evolution at different annular sections of a ϕ 24 mm rebar during water quenching and subsequent air cooling. As can be seen, although temperature gradient exists between centre and surface before cooling, the temperature becomes nearly uniform at all sections after cooling. The centre temperatures of the bar before and after quenching are 1.075°C and 660°C respectively.

Figure 13 shows the volume fraction of different phases at different annular sections across the cross-section of the rebar. 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.

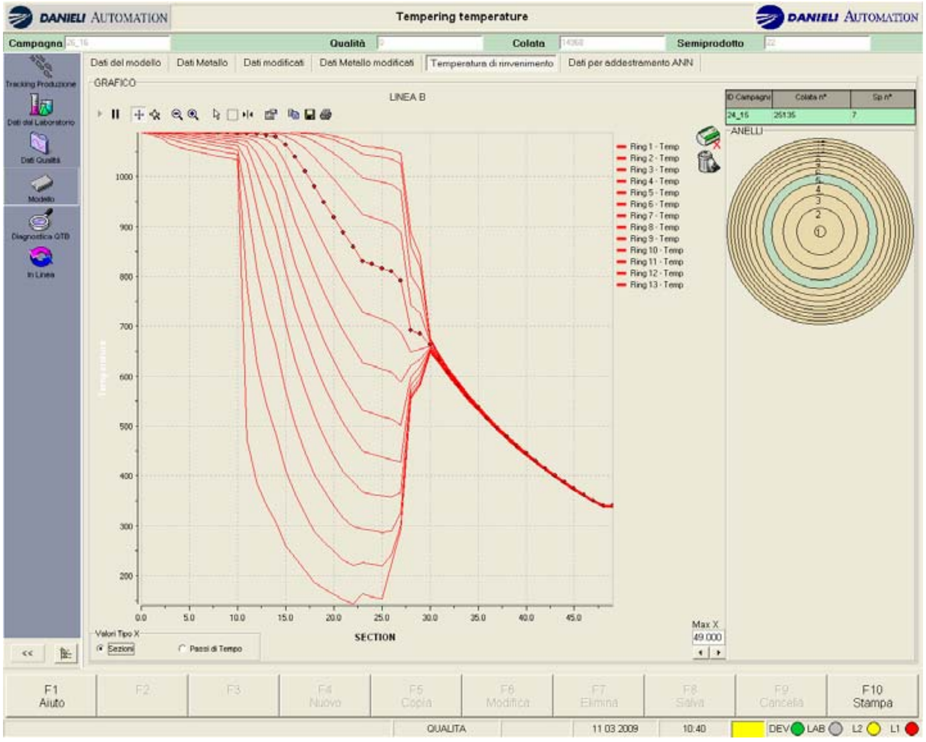
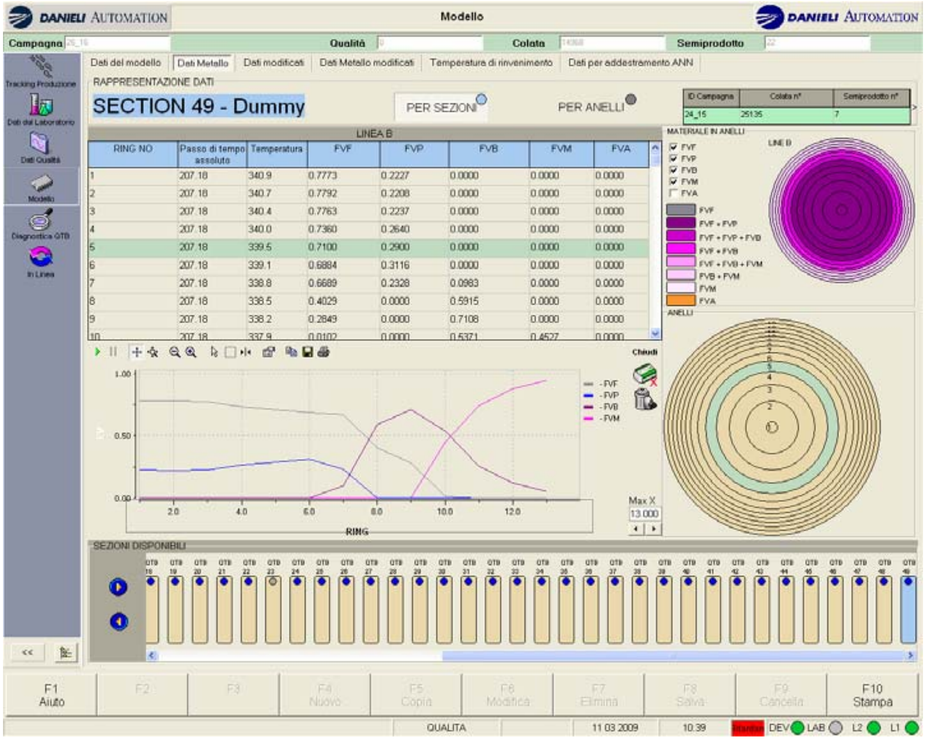


Figure 12. Temperature distribution at different annular sections of rebar during and after quenching.



SECTION 49 - Dummy

LINEA B

RING NO	Passo di tempo assoluto	Temperatura	FVF	FVP	FVB	FVM	FVA
1	207.18	340.9	0.7773	0.2227	0.0000	0.0000	0.0000
2	207.18	340.7	0.7792	0.2208	0.0000	0.0000	0.0000
3	207.18	340.4	0.7763	0.2237	0.0000	0.0000	0.0000
4	207.18	340.0	0.7360	0.2640	0.0000	0.0000	0.0000
5	207.18	339.5	0.7100	0.2900	0.0000	0.0000	0.0000
6	207.18	339.1	0.6884	0.3116	0.0000	0.0000	0.0000
7	207.18	338.8	0.6689	0.2328	0.0983	0.0000	0.0000
8	207.18	338.5	0.4029	0.0000	0.5915	0.0000	0.0000
9	207.18	338.2	0.2849	0.0000	0.7108	0.0000	0.0000
10	207.18	337.9	0.0102	0.0000	0.5371	0.4527	0.0000

Figure 13. Distribution of different phases across the section of a rebar.

4 TESTING AND VALIDATION

Figure 14 shows the average volume fraction of different phases across section of the rebar. From these, the average mechanical properties such as YS, UTS and HV10 are calculated. These are also shown.

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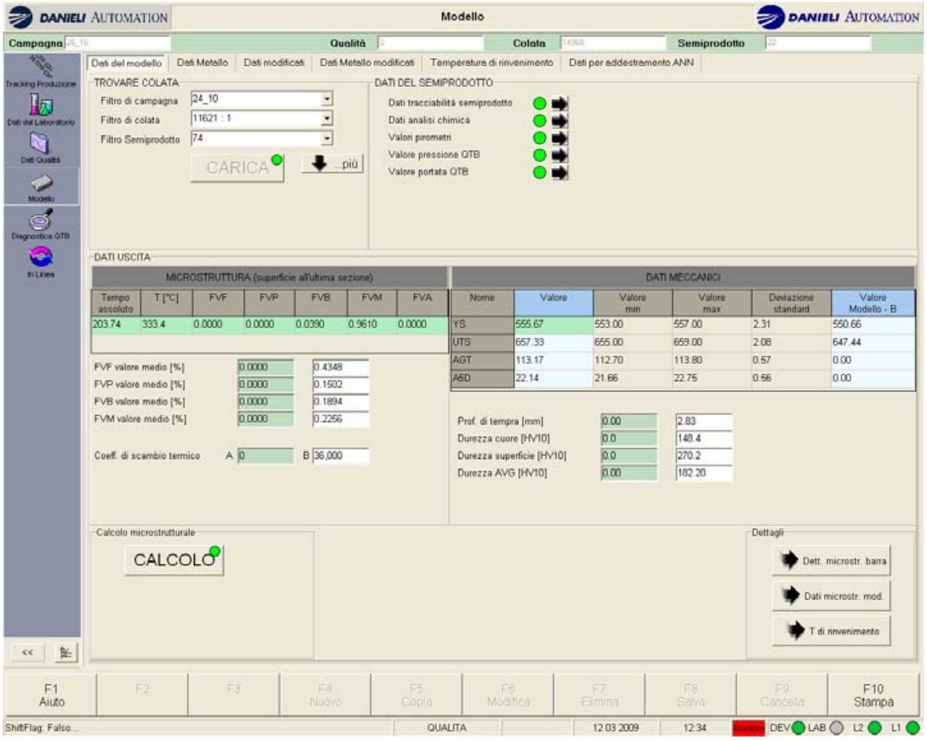

Campagna 25_15 Qualità 0 Colata 14368 Semiprodotto 32

TROVARE COLATA

Filtro di campagna: 24_10
Filtro di colata: 11621 : 1
Filtro Semiprodotto: 74

DATI DEL SEMIPRODOTTO

Dati tracciabilità semiprodotto ●
Dati analisi chimica ●
Valori pirometri ●
Valore pressione QTB ●
Valore portata QTB ●

DATI USCITA

MICROSTRUTTURA (superficie all'ultima sezione)

Tempo assoluto	T [°C]	FVF	FVP	FVB	FVM	FVA
203.74	333.4	0.0000	0.0000	0.0390	0.9610	0.0000

FVF valore medio [%]	0.0000	0.4348
FVP valore medio [%]	0.0000	0.1502
FVB valore medio [%]	0.0000	0.1894
FVM valore medio [%]	0.0000	0.2256

Coeff. di scambio termico A 0 B 36,000

DATI MECCANICI

Nome	Valore	Valore min	Valore max	Deviazione standard	Valore Modello - B
YS	555.67	553.00	557.00	2.31	550.66
UTS	657.33	655.00	659.00	2.08	647.44
AGT	113.17	112.70	113.80	0.57	0.00
A5D	22.14	21.66	22.75	0.56	0.00

Prof. di tempra [mm]	0.00	2.83
Durezza cuore [HV10]	0.0	148.4
Durezza superficie [HV10]	0.0	270.2
Durezza AVG [HV10]	0.00	182.20

Calcolo microstrutturale

Dettagli

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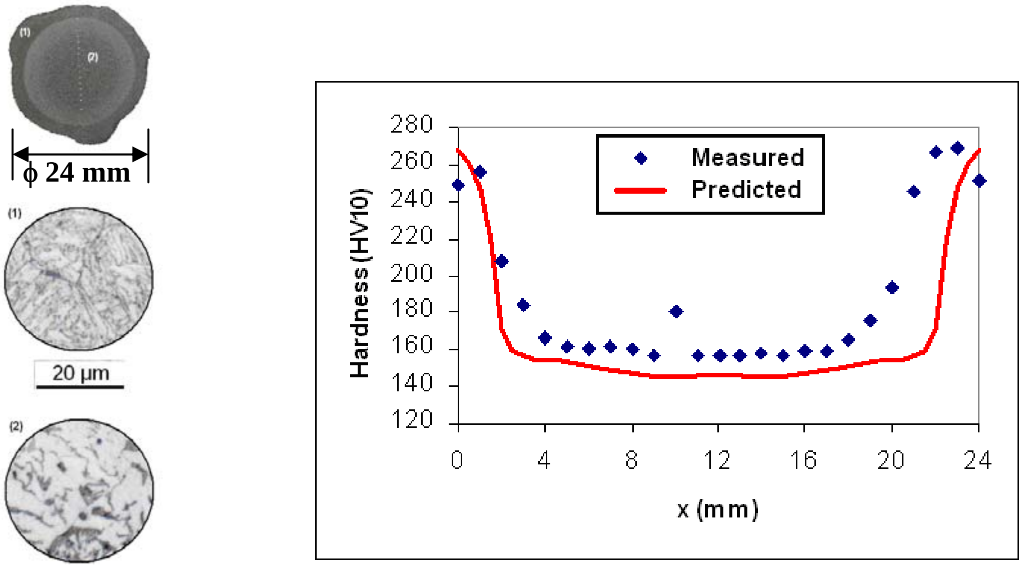
Figure 14. Prediction of microstructure and properties of rebar.

Figure 15a shows the microstructure at the core and the rim of the same rebar. This is obtained through metallographic examination. The rim thickness is also shown. The ferritic-pearlitic core and the tempered martensitic rim are also evident from the micrograph. To verify the hardness profile, micro-hardness test was carried out, and the values at different points are plotted in Figure 15b. The hardness profile predicted from the QTB Plus system is also plotted for comparison.



(a) (b)

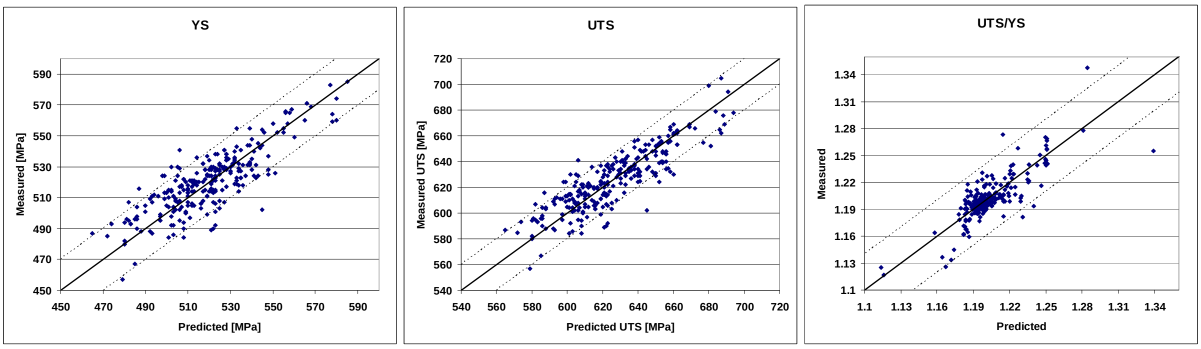
Figure 15. Comparison between Actual and Predicted Structure and Properties of Φ 24 mm rebar - (a) Microstructure; (b) Hardness.

A good match is obtained at all points across section. The rim thickness predicted by the system matches well with that obtained from metallographic examination.

4.1 Accuracy & Reliability

To determine the accuracy and reliability of the system 249 rebar samples were taken between diameters Φ 8 mm – 32 mm for comparison between predicted and actual mechanical properties. 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 equivalents are around 0.4. The YS and EL are more than 450 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 16). The data covers YS range of 450 MPa to 590 MPa, and UTS range of 580 MPa to 700 MPa. Figures 16a and 16b show the comparison between the actual and predicted YS and UTS. 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 16c 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 16. Comparison between Actual and Predicted values of (a) YS; (b) UTS; and (c) UTS/YS ratio.

The standard deviations obtained from the predicted errors of YS and UTS are ± 12.04 MPa, and ± 12.95 MPa respectively. In case of UTS/YS ratio, the standard deviation is ± 0.014.

5 CONCLUSION

The paper illustrates the through-process modeling and control concept between casting and rolling processes. Such integrated approach holds promise for better control of properties of long products in future. Different automation systems in casting and rolling can be integrated to produce superior quality billet and final products. The on-line quality information of billet during casting processes can subsequently be used in the subsequent rolling operation to choose proper rolling strategy for the billet of a given quality to roll to the final dimension. The quality solution at the rolling mill can then ensure the final product quality.

REFERENCES

1 MUKHOPADHYAY, A.; GALASSO, L.M. “DANIELI-QTB Plus – Technology for Quality Improvement of Rebars – Implementation Experience”, South-East Asia Iron and Steel Institute (SEAISI) Conference, 17-20 May 2010, Ho Chi Minh City, Vietnam, pp. 1-11

2 MUKHOPADHYAY, A.; GALASSO, L.M.; ENA, M.; BUZZI, G., “New Technology to meet challenges of High Quality Rebars – DANIELI QTB PLUS”, SEASI ’09 Conference, 18-21 May 2009, Shangri-La Hotel, Kuala Lumpur, Malaysia

3 GUAZZELLI, L.; MUKHOPADHYAY, A.; OMETTO, M., “Danieli Automation LPCS – Liquid Pool Control System to improve quality of continuously cast slabs”, **Danieli Technology Book**, 2010, pp. 254-259

4 KUNDU, S.; MUKHOPADHYAY, A.; CHATTERJEE, S.; CHANDRA, S., **ISIJ International**, vol. 44, no.7, 2004, pp. 1217-1223

5 MUKHOPADHYAY, A., “Automation Technologies for Better Quality Steel”, **Steel and Metallurgy**, Special Feature, March 2010, pp. 32-48

6 MUKHOPADHYAY, A.; GALASSO, L.M., “Implementation of a New Technology for Quality Improvement and Productivity Enhancement of Long Products”, LAMINAÇÃO-2010, Belo Horizonte, Brazil, 26-29 October 2010, pp.154-165

7 MUKHOPADHYAY, A.; GALASSO, L.M., “Technological Trends towards Production of High Quality Rebars, Plain Rounds and Wire Rods”, Proc. Seminar on Rolling Mills and Processing Lines, 27-28 March 2009, Ranchi, India, pp. 106-113

8 MUKHOPADHYAY, A.; GALASSO, L.M., “Automation Systems for Heat Treatment and Controlled Cooling of Plates and Bars”, **La Metallurgia Italiana**, Memorie – Controllo processi, n. 7-8/2010, pp. 15-22

9 MUKHOPADHYAY, A.; GALASSO, L.M.; ENA, M.; BUZZI, G., “QTB PLUS: Better Control for Mechanical Properties of Quenched and Tempered Bars”, AISTech ’09, 4-7 May 2009, America’s Center, St. Louis, USA