MONITORING OF METALLURGICAL PROCESSES DURING HOT ROLLING

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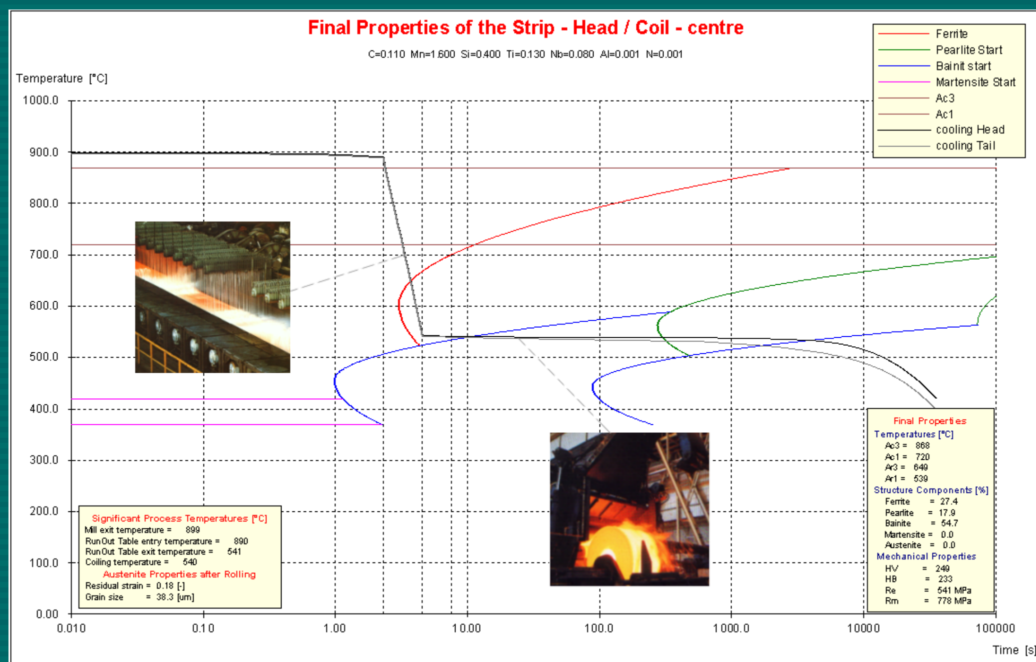
Metallurgical Monitoring
What does it mean?

METALLURGICAL MONITORING

prediction of final mechanical properties of hot rolled steel products coupled with process data being received on-line from the rolling mill control system!



Metallurgical Monitoring

Three possible levels of implementation

It was developed yet !

- **off-line implementation**

  Off-line tool for technologists that enables predictio[...]echanical properties of rolled production based on predefine[...] manually entered rolling technology parameters.

It is being developed for flats !

- **on-line monitoring**

  Similar functionality as off-line level b[...]ed directly to the Level2 of the control system. It enable[...] loading of rolling technology parameters and passive mo[...]of final mechanical properties of whole production.

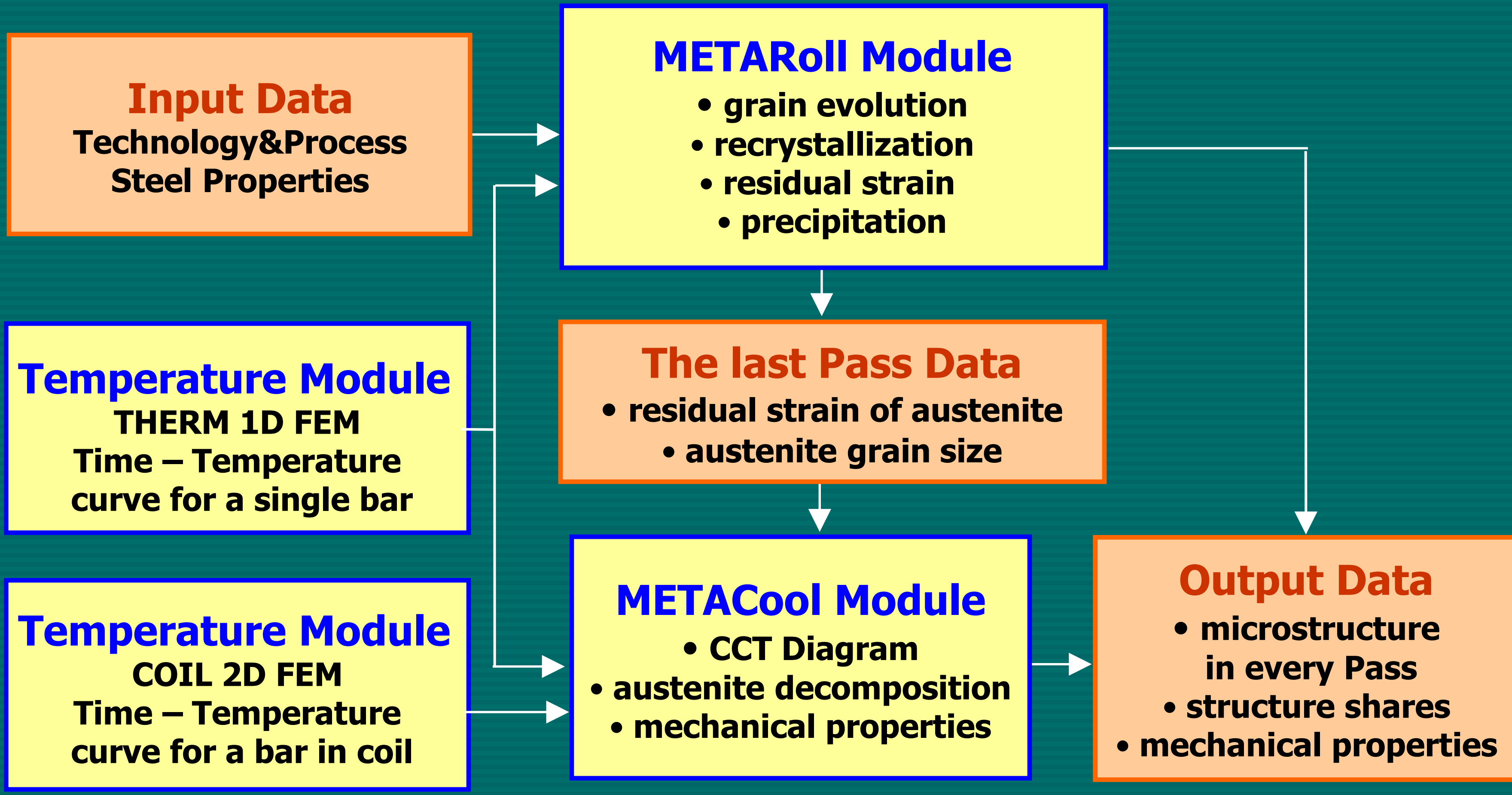
It is planned for the future!

- **on-line control**

  Level2 application that ba[...]rolling conditions sets up cooling strategy to receive reque[...]ed final mechanical properties of rolled product.

Metallurgical Monitoring

Physical based temperature & metallurgical modules



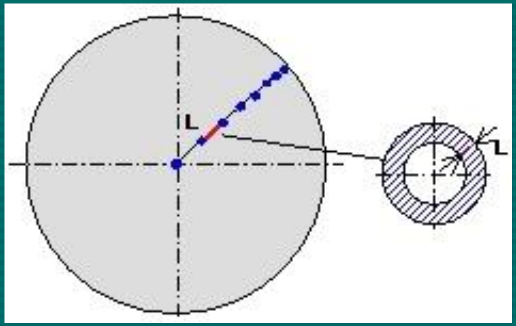
Metallurgical Monitoring

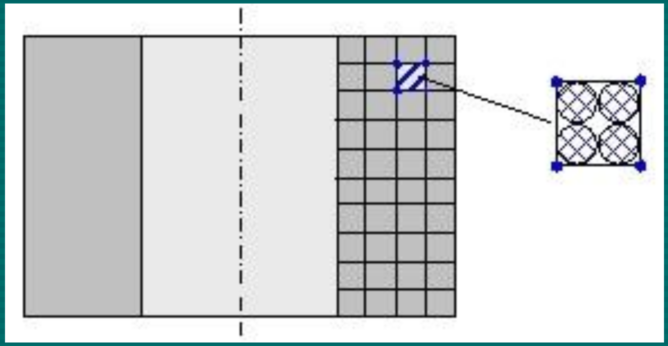
Steel groups and limits of chemical composition

GROUP	C		Mn		Si		Cr		Ni		Mo		V	W	Ti	Nb	B	Al	N
	min	max	min	max	min	max	min	max	min	max	min	max	max	max	max	max	max	max	max
C < 0.06	0.001	0.06	0.05	0.70	0.02	0.30	0	0.10	0	0.10	0	0.10	0.05	-	0.05	0.10	0.004	0.05	0.015
C < 0.20	0.06	0.25	0.20	1.50	0.05	1.50	0	0.40	0	0.25	0	0.10	0.10	-	0.05	0.10	0.004	0.05	0.015
C < 0.50	0.20	0.55	0.20	1.50	0.05	1.50	0	0.40	0	0.25	0	0.10	0.10	-	0.05	0.10	0.004	0.05	0.015
C < 0.95	0.50	1.15	0.20	1.50	0.05	1.50	0	0.40	0	0.25	0	0.10	0.10	-	0.05	-	0.004	0.05	0.015
Mn	0.10	0.50	1.50	2.00	0.05	1.50	0	2.0	0	0.25	0	0.10	0.25	-	-	0.10	0.004	0.05	0.015
Cr C < 0.6	0.15	0.65	0.20	1.20	0.05	0.40	0	1.50	0	0.25	0	0.10	0.40	-	-	-	0.004	0.05	0.015
Cr C > 0.6	0.60	1.15	0.20	1.20	0.05	0.40	0	1.50	0	0.25	0	0.10	0.40	-	-	-	0.004	0.05	0.015
Mo	0.15	0.55	0.40	1.20	0.05	0.40	0	0.40	0	0.25	0	0.40	-	-	-	-	0.004	0.05	0.015
Cr-Mo	0.15	0.65	0.40	1.00	0.05	0.40	0	1.50	0	0.25	0	0.40	-	-	-	-	-	0.05	0.015
Cr-Si	0.45	0.70	0.20	2.00	1.00	2.00	0	1.50	0	0.25	0	0.10	0.10	-	-	-	-	0.05	0.015
Ni-Cr-Mo	0.15	0.65	0.40	1.00	0.05	0.40	0	1.50	0	3.50	0	0.40	-	-	-	-	-	0.05	0.015

Metallurgical Monitoring – Theoretical Background
FEM Temperature calculations

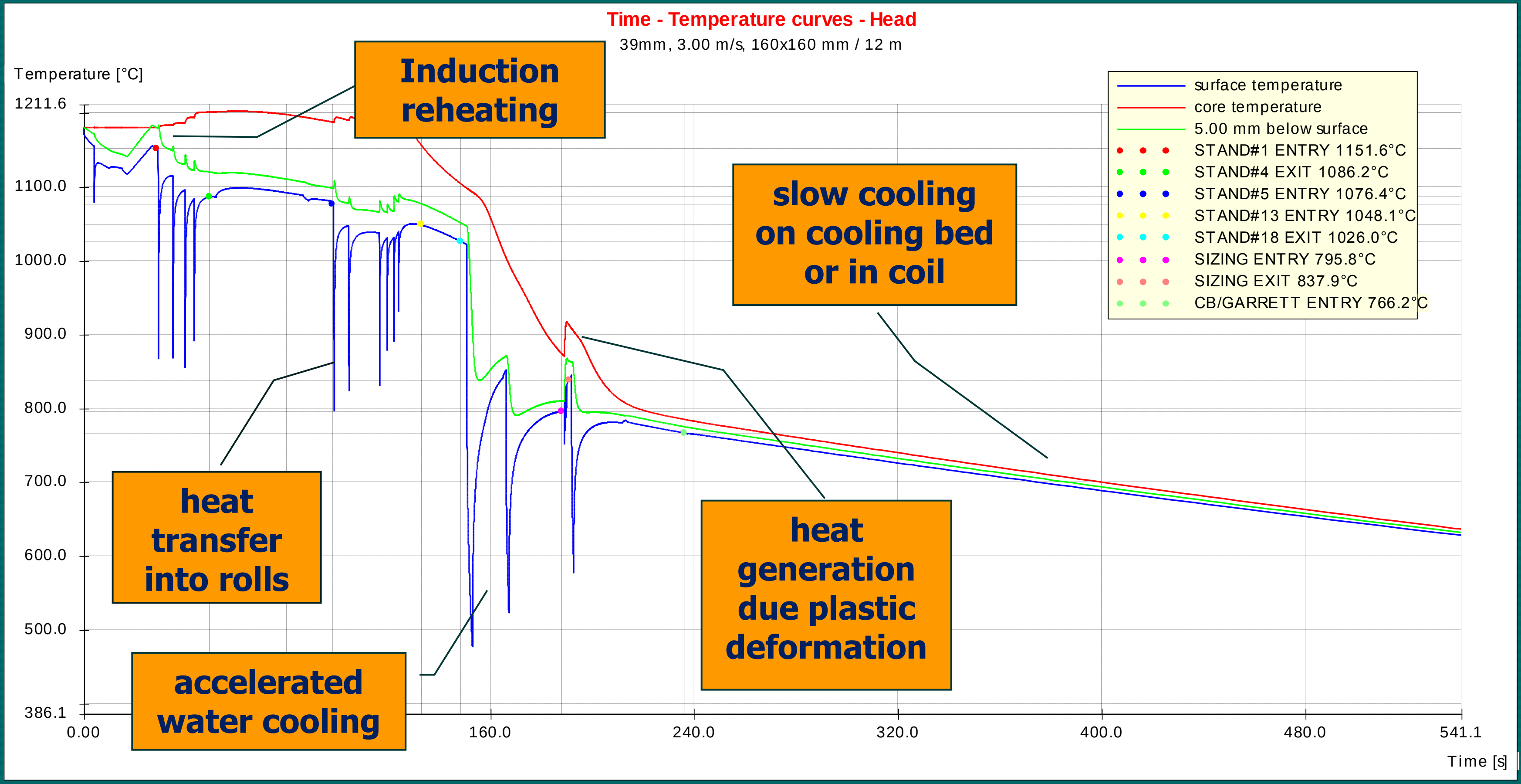
- **Therm 1D** -> nonstationary heat transfer FE analysis for 1D axisymmetric bodies (linear 2-node ring)
- **Coil 2D** -> nonstationary heat transfer FE analysis for 2D plane axisymmetric bodies (linear 4-node quadrangle)
- **Model of thermal properties** -> thermal conductivity, density and specific heat depend on the coil temperature and its tightening
- **Heat transfer** -> time and temperature dependent heat transfer coefficient and ambient temperature





Metallurgical Monitoring – Theoretical Background

FEM Temperature calculations



Metallurgical Monitoring – Theoretical Background

MetaROLL Module – Metallurgy during rolling

Chemical composition

Process parameters in every pass:
- **temperatures**
- **strains**
- **strain rates**

Activation energy of recrystalization
Zenner-Hollomon parameter

Increasing of the activation energy in case of precipitation

Recrystallized part Xrex for given temperature, effective strain and time available between neighbouring passes

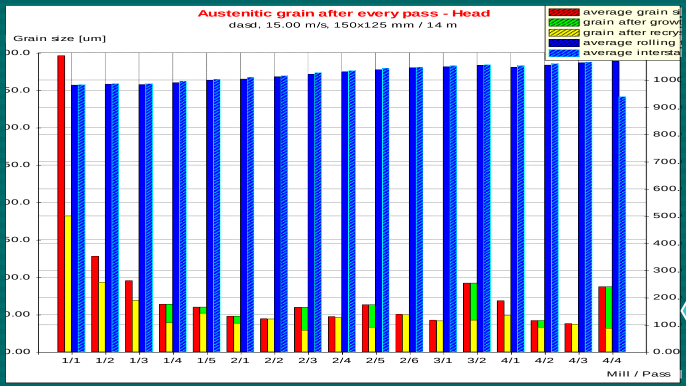
Residual strain

FIrest = FIef *(1 - Xrex)

Size of recrystallized grain of austenite

Growth of recrystallized grain between particular passes

! pure physical approach !



Metallurgical Monitoring – Theoretical Background

MetaCOOL Module – Metallurgy after rolling - Step 1

CCT Diagram Prediction

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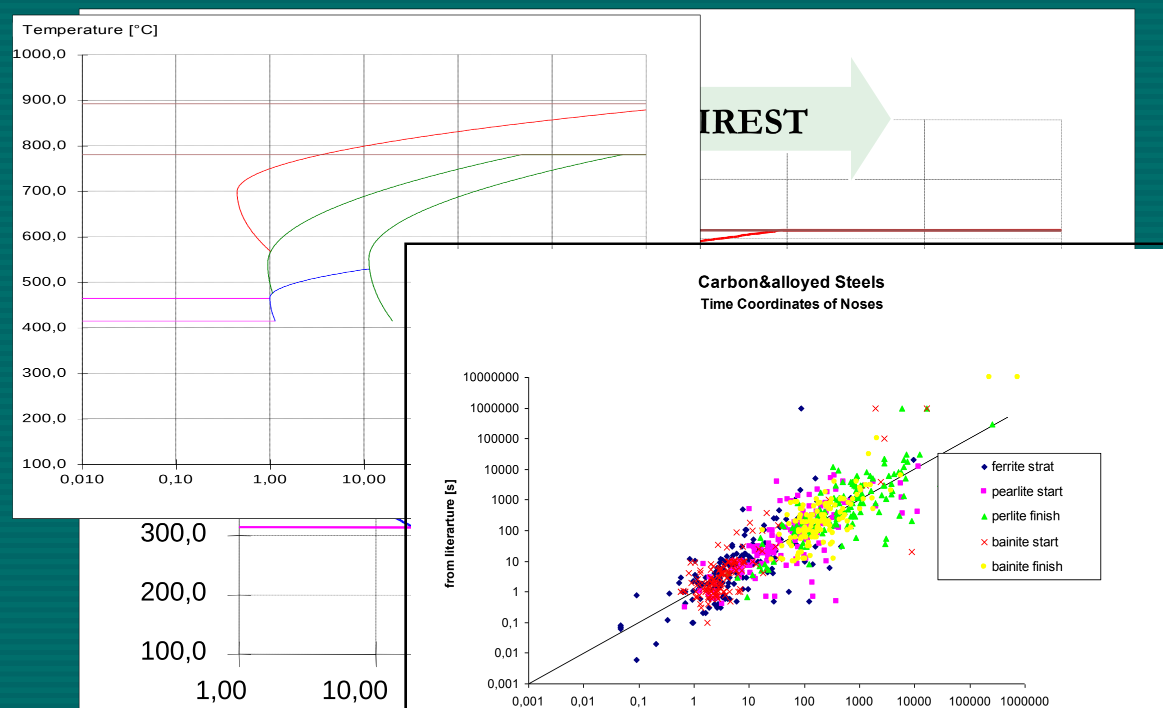
Structure Shares Calculation

↓

Mechanical Properties Calculation



Linear multiparametric regression

S(i) = exp (Bo + ∑ (B(i) . C(i))

T(i) = Ao + ∑ (A(i) . C(i))

$\mathrm{Sx} = \mathrm{Sox} \cdot \mathrm{A_S} \cdot \exp((-\mathrm{B_S} + \mathrm{C_S} \cdot \mathrm{C} \ldots {}^{/3})) \cdot \exp(F_S \cdot B)$

Metallurgical Monitoring – Theoretical Background

MetaCOOL Module – Metallurgy after rolling - Step 2

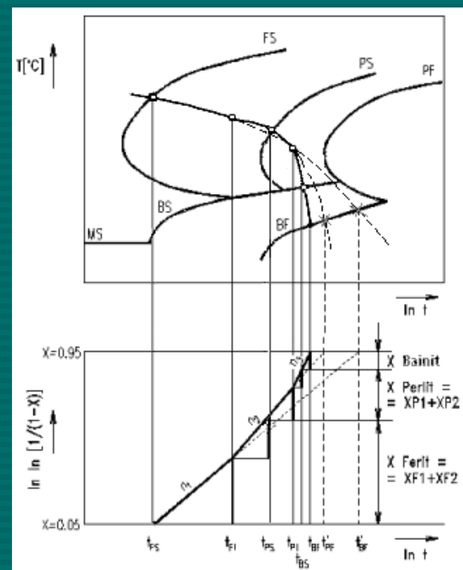
CCT Diagram Prediction

↓

Structure Shares Calculation

↓

Mechanical Properties Calculation



Avrami equation for pearlite and bainite transformation

$$X_i(t,T) = (1 - \exp(-k \cdot t^n)) \cdot X_\gamma$$

Koistinen-Marburger equation for martensite transformation

$$Xm(T) = (1 - \exp(-b \cdot (T_{Ms} - T)^n)) \cdot X_\gamma$$

Metallurgical Monitoring – Theoretical Background

MetaCOOL Module – Metallurgy after rolling - Step 3

CCT Diagram Prediction

↓

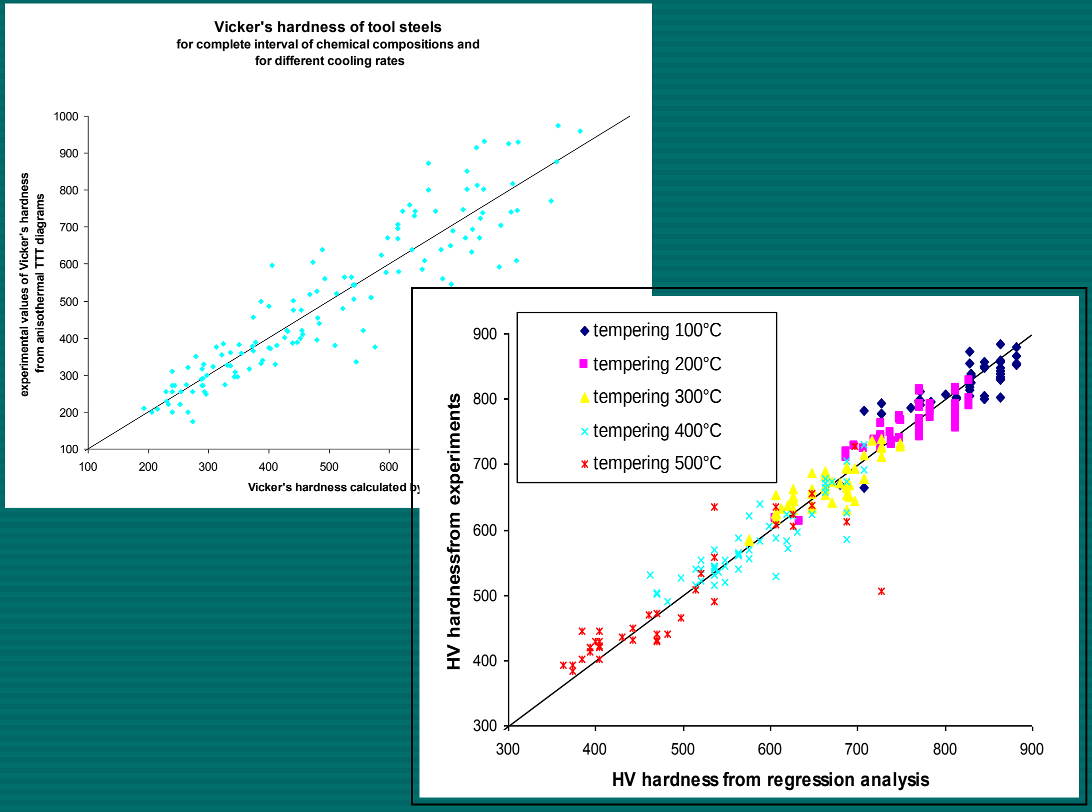
Structure Shares Calculation

↓

Mechanical Properties Calculation

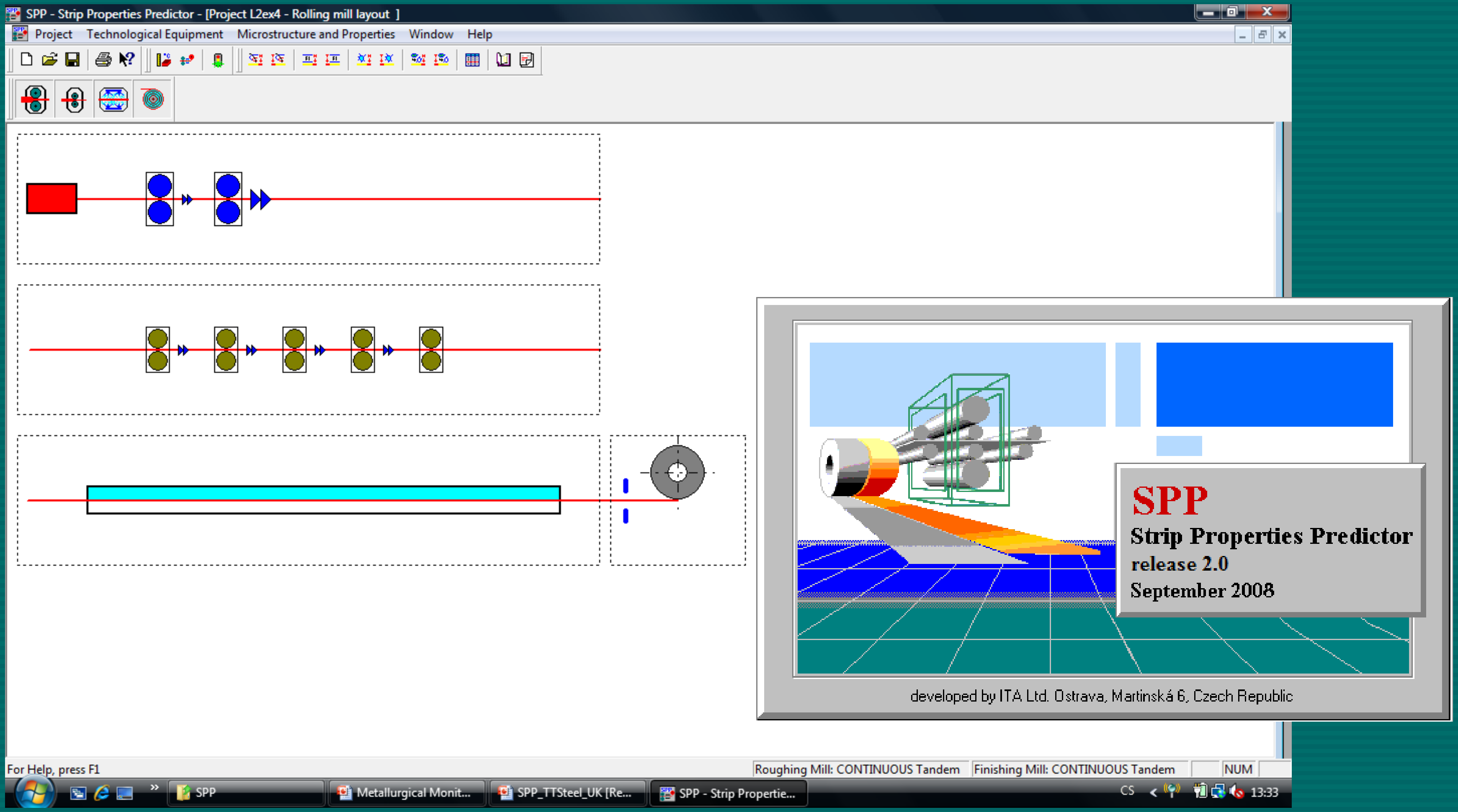
Linear regression

$$HV = C_O + \%Fe * \Sigma (C1_{i} * c_i) + \%Pe * \Sigma (C2_{i} * c_i) + \%Ba * \Sigma (C3_{i} * c_i) + \%Ma * \Sigma (C4_{i} * c_i)$$



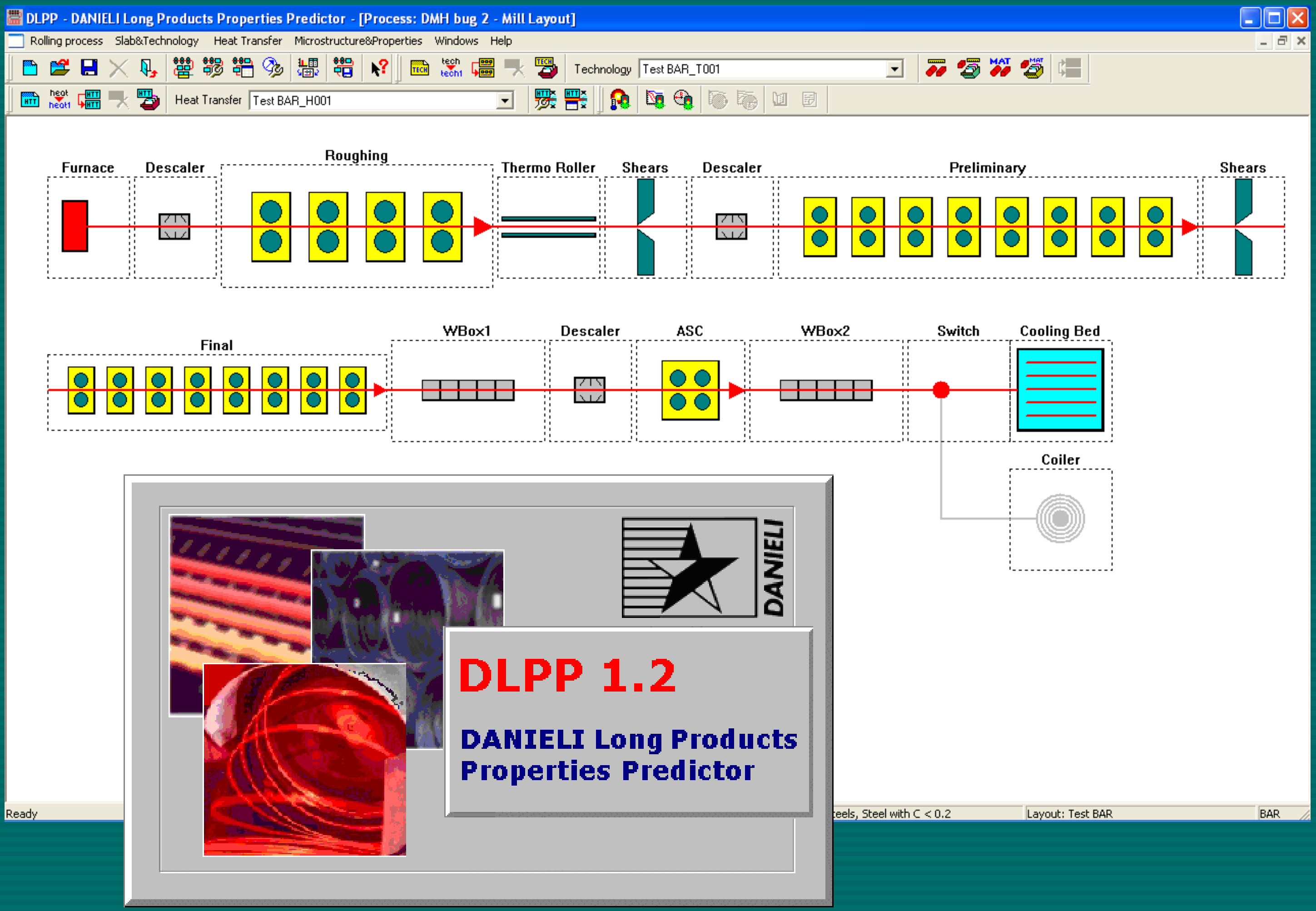
Metallurgical Monitoring – Off-line implementation

SPP software – Strip Properties Predictor



Metallurgical Monitoring – Off-line implementation

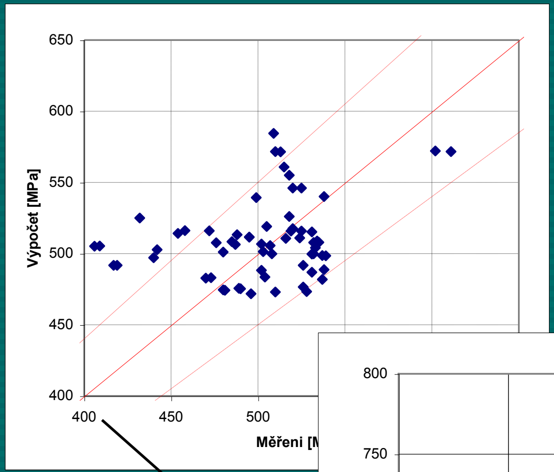
DLPP software – Danieli Long Products Properties Predictor



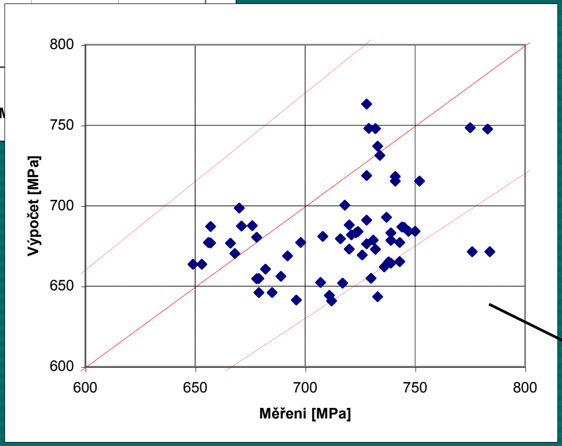
Off-line implementation

DLPP software – Verification for WIRE ROD rolling

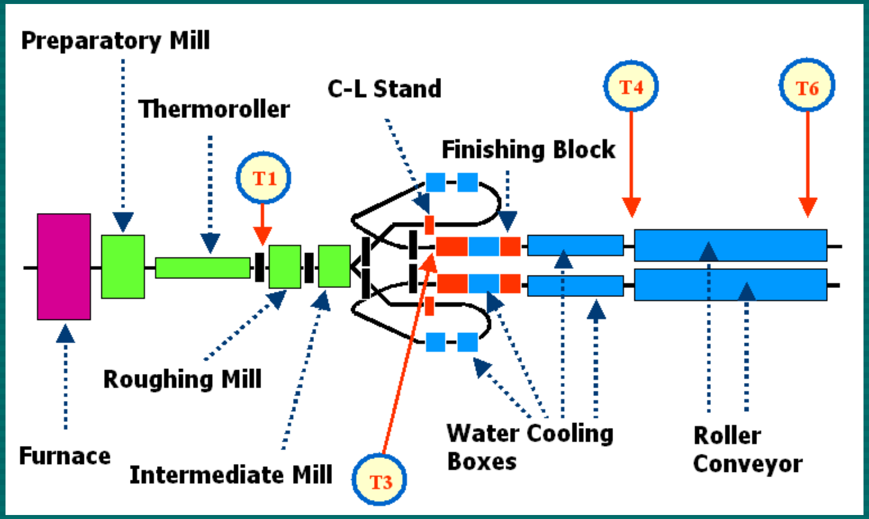
(64 pcs) various diameters	C	Mn	Si	Cr	Ni	Ti	B
	0.403	0.64	0.26	0.06	0.02	0.002	0.0002



Yield Stress



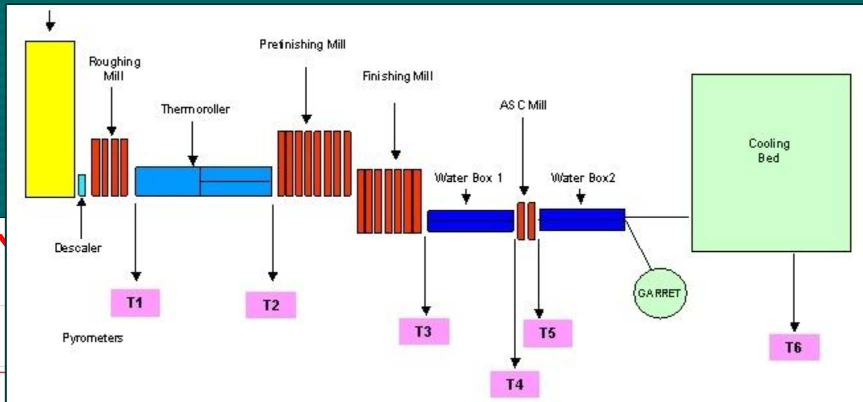
Ultimate Tensile Strength

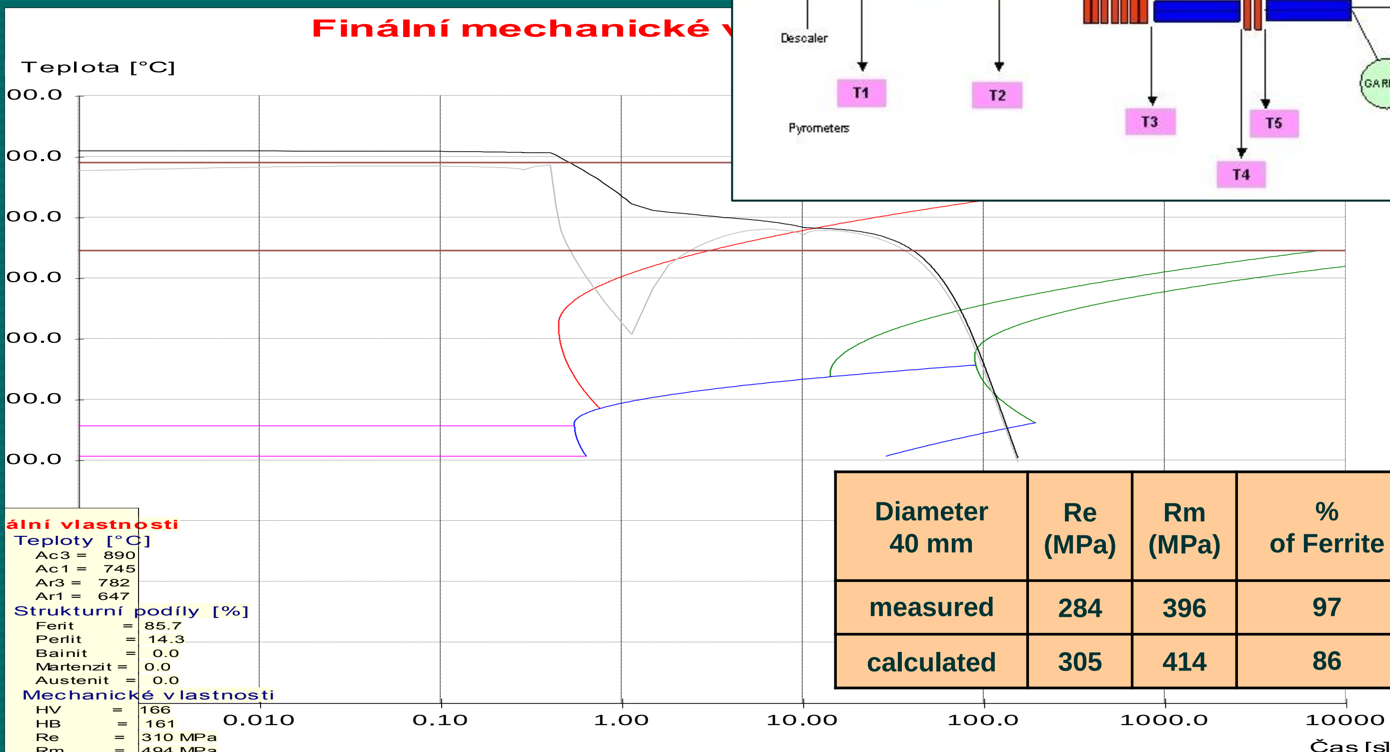


Off-line implementation

DLPP software – Verification for BAR rolling

C	Mn	Si	Ti
0.065	0.6	0.2	0.15



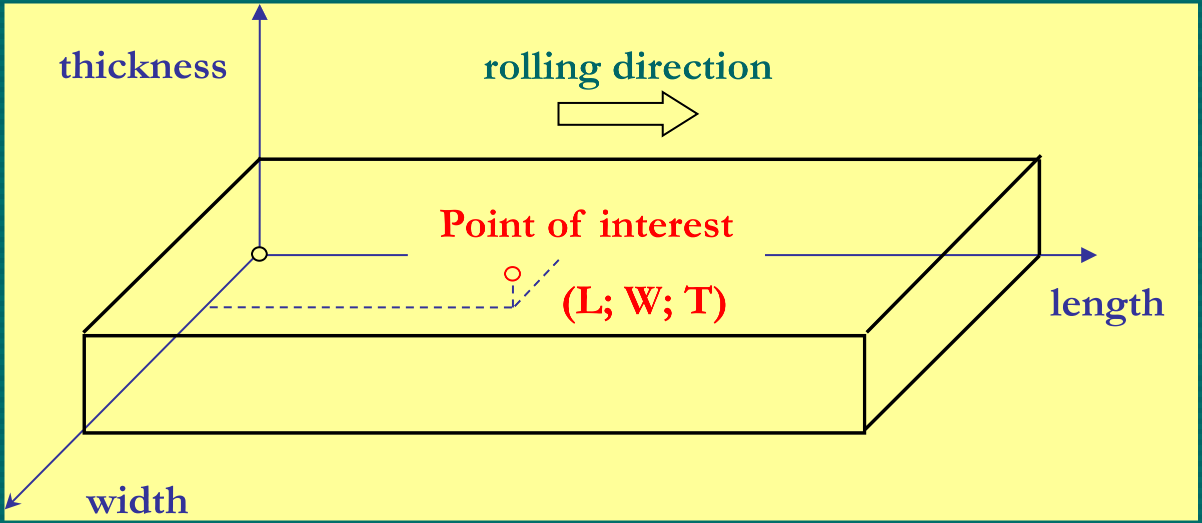


Diameter 40 mm	Re (MPa)	Rm (MPa)	% of Ferrite	% of Pearlite
measured	284	396	97	3
calculated	305	414	86	14

On-line Monitoring

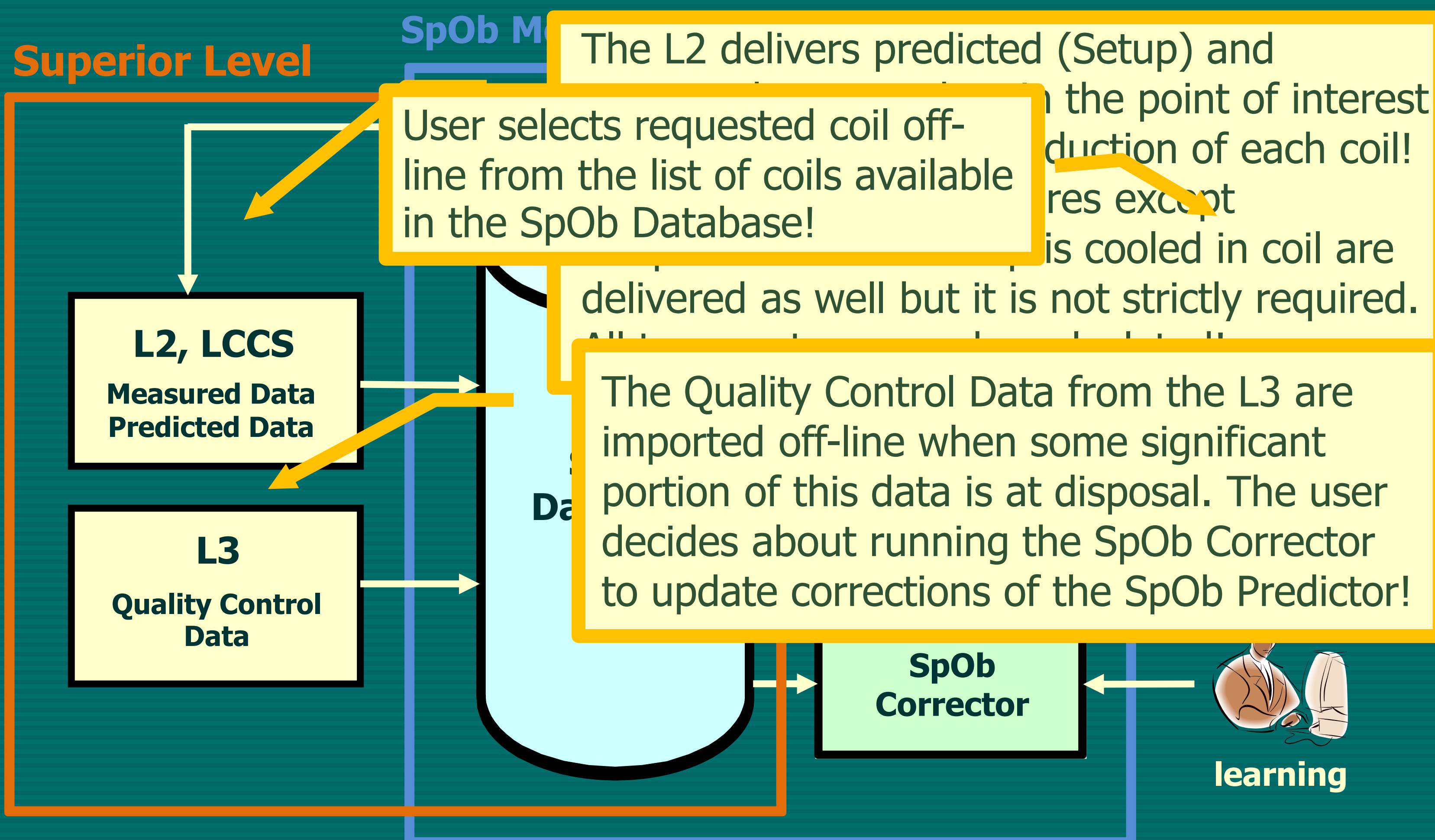
An example for Hot Strip Mill - Strip Observer Monitor

Strip Observer Monitor predicts final mechanical properties of hot rolled strip in coil in one point of interest from process data being received on-line from the rolling mill control system.



On-line Monitoring

Strip Observer Monitor – Basic chart



On-line Monitoring

Strip Observer Monitor – Cooling of strip in coil

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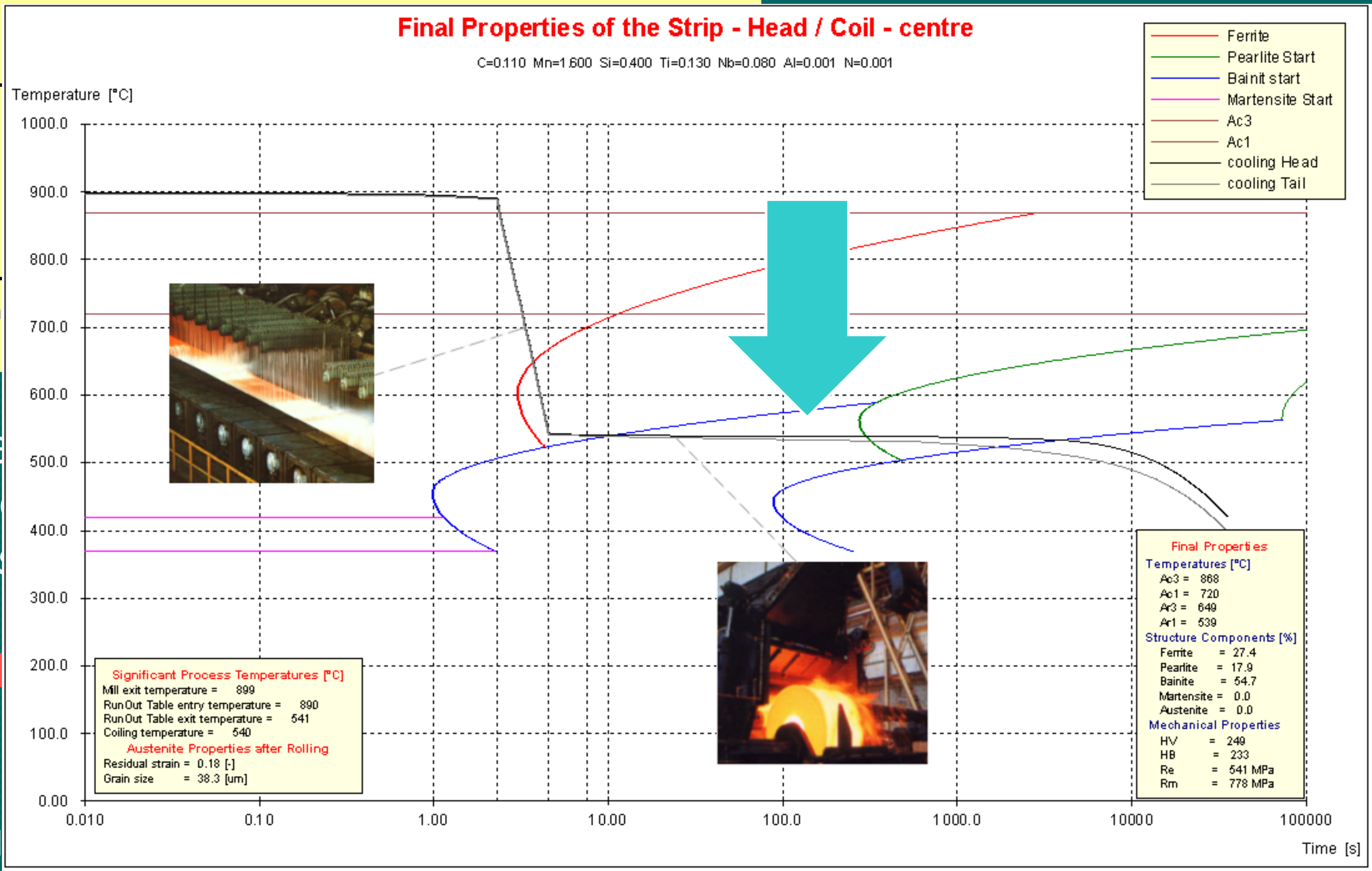

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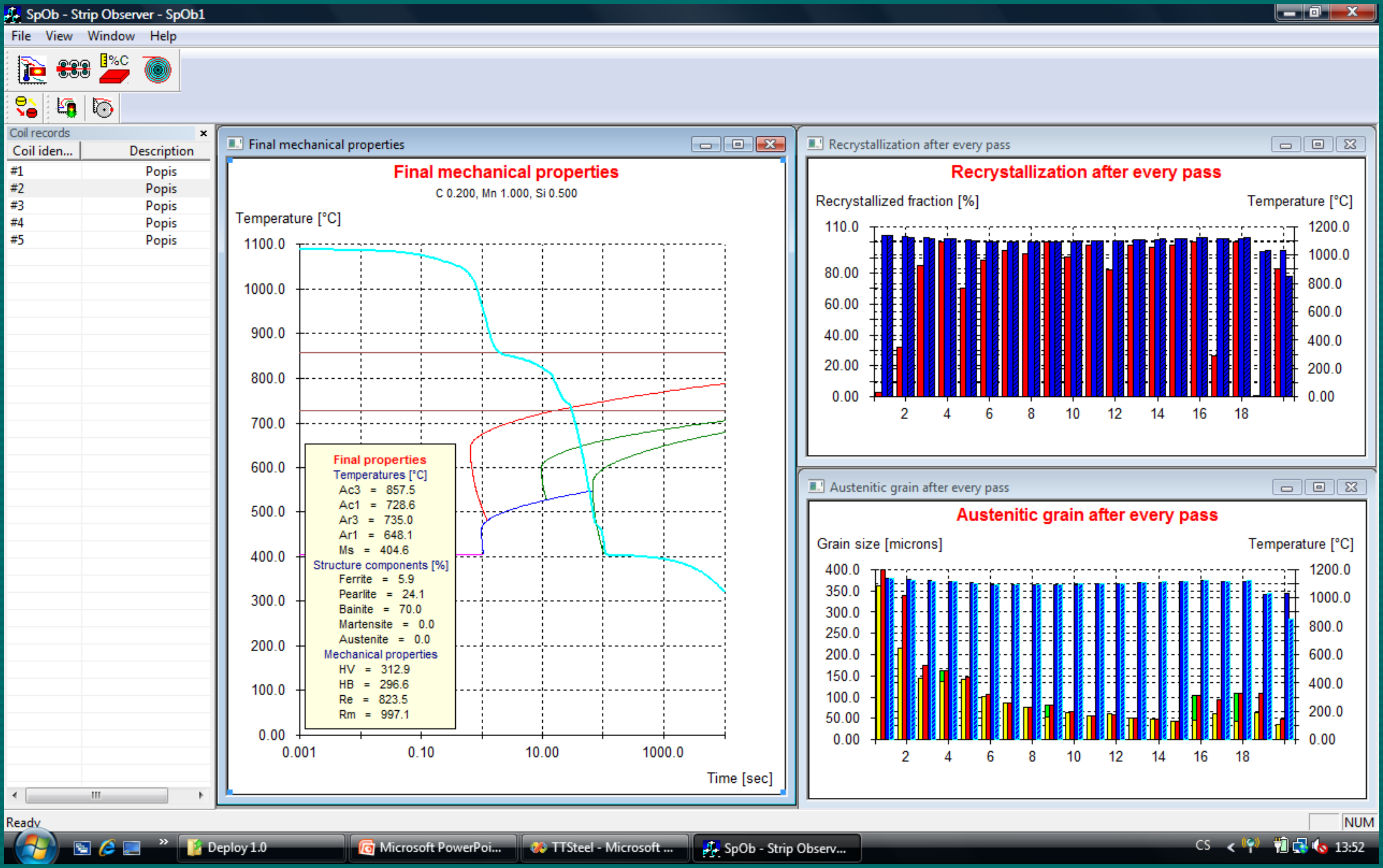
module but for fixed coil dimensions.

On-line Monitoring

Strip Observer Monitor – SW Implementation



On-line Monitoring
Data Interface – Strip Data

```
SPOB_CHEM_COMPOS
         chemCompos;
double dThickness;
double dLength;
double dWidth;
double dLengthCoord;
double dWidthCoord;
double dThicknessCoord;
int nLayer;
double *dTau;
double *dTempLeftEdge;
double *dTempCentre;
double *dTempRightEdge;
Double dInDiameter;
double dOutDiameter;
```

chemCompos	Chemical composition
	`double C, Mn, Si, Cr,V, Ti, Nb, Al, N, Mo, Ni, B, W, P, S, Cu, As, Sn, Co;`
	and initial grain size of austenite of steel
	`double Grain;`

dThickness	Strip thickness in mm.
dWidth	Strip width in mm.
dLength	Strip length in mm.
dLengthCoord	Relative coordinate of the point of interest along strip length.
dWidthCoord	Relative coordinate of the point of interest along strip width.
dThicknessCoord	Relative coordinate of the point of interest along strip width.
nLayer	Number of strip lengthwise segments.
**dTau*	Coiling times of each strip segment in sec.
**dTempLeftEdge*	Lengthwise averaged temperature of the left edge of each strip segment before coiling in C.
**dTempCentre*	Lengthwise averaged temperature in the centre of each strip segment before coiling in C.
** dTempRightEdge*	Lengthwise averaged temperature of the right edge of each strip segment before coiling in C.
dInDiameter	Inner diameter of the coil in mm.
dOutDiameter	Outer diameter of the coil in mm.

On-line Monitoring

Data Interface – Rolling Technology Data

```
int nPass;
double   *dFI;
double   *dRate;
double   *dTVA;
SPOB_CURVE  dTPC;
double   MTemp_Furnace;
double   MTemp_MH1;
double   MTemp_MH2;
double   MTemp_MH3;
double   MTemp_MH4;
double   MTemp_MH5;
```

nPass	Number of passes.
**pFI*	Logarithmic strain in each pass.
**pRate*	Strain rate in each pass in s-1.
**pTempTVA*	Rolling temperature in each pass in C.
dTPC	Temperature curve between passes.
MTemp_Furnace	Measured temperature in the Stossofen1 in C.
MTemp_MH1	Measured temperature in the Messhaus1 in C.
MTemp_MH2	Measured temperature in the Messhaus2 in C.
MTemp_MH3	Measured temperature in the Messhaus3 in C.
MTemp_MH4	Measured temperature in the Messhaus4 (exit rolling temperature) in C.
MTemp_MH5	Measured temperature in the Messhaus5 (coiling temperature) in C.

On-line Monitoring
Special module 1

Beginning of austenite transformation during rolling:

```
int SpOb_CalcTransf(
        const SPOB_MAIN_INPUT *pMainInput,
        const int nResultCount,
        SPOB_TRANSFORMATION_RESULT *pResults,
        int *pPassNumber);
```

const SPOB_MAIN_INPUT *pMainInput	Input data structure containing information about rolling process parameters in the point of interest
const int nResultCount	Number of passes
SPOB_TRANSFORMATION_RESULT *pResults	Output data structures containing information about austenite transformation in the point of interest in each pass
int *pPassNumber	Index of the pass where austenite transformation in the point of interest started

Metallurgical Monitoring

Special module 2

Full automatic regime of metallurgical calculations:

```
int SpOb_AutomaticCalc(
      const SPOB_MAIN_INPUT  *pMainInput,
      const SPOB_COIL_INPUT  *pCoilInput,
      SPOB_PROPERTIES_RESULT *pResult);
```

const SPOB_MAIN_INPUT *pMainInput	Input data structure containing information about rolling process parameters in the point of interest
const SPOB_COIL_INPUT *pCoilInput	Input data structure containing information about cooling of the strip in coil
SPOB_PROPERTIES_RESULT *pResult	Output data structure containing calculated microstructure shares and mechanical properties of strip in the point of interest

Metallurgical Monitoring
Summary

• the software SPP and DLPP has been developed for off-line computer simulation of metallurgical processes in hot rolled strips, bars and wire rods during rolling and after subsequent cooling!

• the SpOb software has been developed for prediction of final mechanical properties of hot rolled strips coupled with process data being received on-line from the rolling mill control system!

• based on specified steel chemistry and rolling technology these software tools predict microstructure parameters of deformed austenite after rolling, especially grain size, recrystallized fraction and retained strain!

• based on specified steel chemistry, microstructure of deformed austenite and cooling strategy these software tools predicts secondary structure shares and corresponding mechanical properties of final product!

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thanks
for your
attention!