CONTROL STRATEGIES FOR INLINE HEAT TREATMENTS IN HOT STRIP PROCESSING OF INNOVATIVE STEEL MATERIALS[1]

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Abstract
Heat treatment of steel is used to adjust different microstructures and mechanical properties. The Quenching and Partitioning (Q&P) process or cyclic annealing for grain refinement lead to increased strength and ductility. Both approaches demand a strict temperature control and a close strip temperature tracking. A control strategy for optimal properties is developed. Herefore a one-stand laboratory scale hot rolling process line was equipped with a water-cooling section and an induction heating device. A detailed temperature control during the process was established accounting for strip thickness and velocity, set-point temperatures and amount of water cooling. While industrial set-points and parameters of closed-loop controllers are often empirical, the presented control system and strategies are investigated by MatLab-Simulink. The improved material properties were evaluated in annealing tests. The control system for the cooling track reduces the temperature gradient within the strip to 12 K. The simulation of the heating track gives an optimal set point. As a prerequisite for a controlled design of time-temperature-cycles it can be calculated for various process parameters. Grain sizes < 5 µm are achieved by cyclic annealing. Accordingly strength and ductility increase. The Q&P treatment produces tempered martensite and retained austenite with improved mechanical properties.
Keywords: Temperature control; Heat treatment; Steel.

ESTRATEGIAS DE CONTROLE PARA TRATAMENTO TERMICO INLINE NO PROCESSAMENTO DE CHAPAS A QUENTE DE ACOS INOVADORES

Abstract
Tratamentos térmicos de aços são utilizados para ajustar microestruturas e propriedades mecânicas. A Têmpera e Particionamento (T&P) ou o processo de recozimento cíclico para refino de grão levam a um aumento de resistência e ductilidade. Ambas exigem um rigoroso controle e sistema de acompanhamento da temperatura da chapa. Uma estratégia de controle é desenvolvido. Um processo de laminação a quente em escala laboratorial foi equipado com uma seção de resfriamento a água e um dispositivo de aquecimento indutivo. Um controle da temperatura durante o processo foi estabelecida para espessura da chapa, temperaturas iniciais e quantidade de água. Enquanto temperaturas e parâmetros dos controladores industriais são muitas vezes empíricos, o sistema de controle e estratégias apresentadas são investigados pelo MatLab-Simulink. Melhoras nas propriedades do material foram avaliados em testes de recozimento. O sistema para o resfriamento reduz a temperatura dentro da chapa em 12 K enquanto simulações do aquecimento proporcionam pontos de ajustes ideais. As condições para um projeto controlado de tempo-temperatura cíclico podem ser calculadas para diferentes parâmetros. Tamanhos de grãos inferiores a 5 µm são obtidos por recozimento cíclico. Conseqüentemente, resistência e ductilidade aumentam. O tratamento térmico T&P produz martensita temperada e austenita retida com melhoras nas propriedades mecânicas.
Palavras-chave: Controle de temperatura; Tratamento térmico; Aço.

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1 MOTIVATION

Innovative heat treatments of steel like the "Quenching and Partitioning" or the cyclic annealing process neccesitate an accelerated cooling. During the fast cooling process, the steel may undergo various phase transformations. Modern steels consist of multiple phases which depend on the temperature-time history of cooling and define the final properties. For the controlled design of the microstructure and the corresponding mechanical features a strict temperature control and an optimal strip temperature tracking are mandatory.

In this project the cooling control strategy and the strip properties will be analyzed for the application on a roll-out table of a hot rolling mill. A laboratory hot rolling process line has been equipped with a water cooling section. A precise temperature track guideline and the process time are a function of the strip thickness and velocity. These parameters are the main criteria for the amount of water.

A strategic management for the cooling track has been investigated. The results will be illustrated by numerical simulations and trial runs on a laboratory hot rolling process line. The material properties of the heat treated steel are evaluated by laboratory annealing experiments. The goal is an integrative strategy for the development of advantageous multiphase steel by controlled cooling.

2 SETUP OF CONTROL STRATEGY

2.1 Model

Cooling is based on loss of heat through heat conduction, convection and heat flux. In this model heat convection between water and strip is elementary.[1,2] But heat transfer also takes place between the strip and the surrounding by radiation, and within the strip as well. All these phenomena are considered in the investigated model. For the development of the control system, a finite dimensional model of the partial differential fourier equation (Eq. 1) is derived.

$$\rho \cdot c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \cdot \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k \cdot \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k \cdot \frac{\partial T}{\partial z}\right)$$

Equation 1. Fourier equation

c_p	thermal capacity [kJ/kgK]
ρ	specific gravity [kg/m³]
κ	thermal conductivity [W/Km]
T	temperature (°C)
t	time (s)
x,y,z	coordinates

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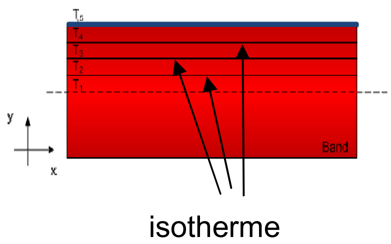

Figure 1. The layer model.[3]

The half thickness of the strip is divided into n-1 layers as shown in Fig. 1. Symmetric cooling on both top and bottom surface of the strip is assumed. This is a typical layer model. It is manifested that the centerline temperature is T_1 and the surface temperature is T_4. With defining $T = [T_1-T_{oo}, T_2-T_{oo},\dots,T_n-T_{oo}]$, the finite difference equation is denoted to the matrix form given in Eq. 2:

$$\dot{T} = AT + B(t,T)\alpha$$

$$A=\begin{bmatrix} a_1 & a_2 & a_3 & 0 \\ a_4 & a_5 & a_6 & 0 \\ 0 & a_4 & a_5 & a_6 \\ 0 & a_7 & a_8 & a_9 \end{bmatrix} B=\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & a_{10} \end{bmatrix}$$

$$a_1 = -\frac{7}{2}\gamma; a_2 = 4\gamma; a_3 = -\frac{1}{2}\gamma; a_4 = \gamma;$$

$$a_5 = -2\gamma a_6 = \gamma; a_7 = -\frac{1}{2}\gamma; a_8 = 4\gamma; a_9 = -\frac{7}{2}\gamma;$$

$$\gamma = \frac{k}{\rho \cdot c_p \cdot (\Delta y)^2}; a_{10} = -\frac{3 \cdot A}{m \cdot c_p}$$

T	layer temperatures [°C]
t	time [s]
α	heat transfer [W/m²K]
k	thermal conductivity [W/Km]
ρ	specific gravity [kg/m³]
c_p	thermal capacity [kJ/kgK]
*Δ*y	layer gap [m]
A	surface area [m²]
m	mass [kg]

Equation 2. Matrix form of the temperature model [3]

This equation system is used to calculate the temperature of each layer of the strip. The temperature of the layer depends on the initial temperature, the heat transfer coefficient and the time. In Fig. 2, the temperature distribution is shown for a constant heat transfer coefficient of 1000 W/m²K and a cooling time of two seconds. The strip thickness is 3 mm. The controlling element of the cooling track is the heat transfer coefficient. By varying this coefficient the cooling of the strip will change.

2.2 Control

The system of the model gives the possibility to use a control system based on the state regulator. The main priority is to optimise the control settings. The state-space approach characterizes the differential equation (which describes the interaction of the systems in different states) as a compound of matrices. With the actual system equation (Eq. 2), already displayed in the matrix form, the state-space form can be established with modest adjustments.

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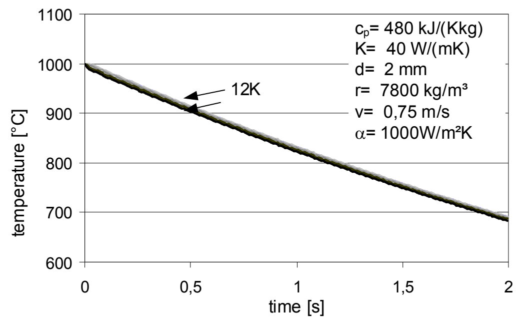

Figure 2. Temperature distribution inside the strip.

$$A=\begin{bmatrix} a_1 & a_2 & a_3 & 0 \\ a_4 & a_5 & a_6 & 0 \\ 0 & a_4 & a_5 & a_6 \\ 0 & a_7 & a_8 & a_9 \end{bmatrix} \quad B=\begin{bmatrix} 0 \\ 0 \\ 0 \\ a_{10} \end{bmatrix} \quad C=\begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \quad x(t)=\begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix} \quad \begin{matrix} u(t)=\alpha(t) \\ y(t)=T_4 \end{matrix}$$

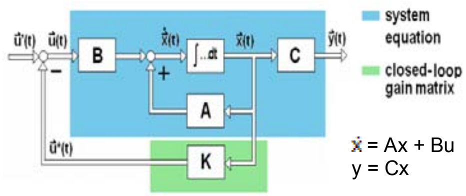

Figure 3. State-space model with Riccati approach.

The control guides the process with the aid of a closed-loop gain matrix (Fig. 3). This gain matrix has to transform all starting conditions to a specific final state.

A basic cooling control concept is the Linear-quadratic Gaussian Method (LQG).[4] This concept solves the system with the feedback matrix K on the base of the Riccati equation. This control approach is the designing tool for a modern state-space technique with optimal dynamic regulators. It is capable of regarding process disturbances with regulation performance and control effort. LQG design requires a state-space representation of the system, that is to be controlled.

So the state model is evident for the generation of reasonable operating points as well as for the observer which should be installed in the Process Logical Control (PLC).

The keynote is the minimisation of a quadratic performance criterion by the gain matrix. Based on this gain matrix, an optimal operating point controller can be calculated and incorporated in the control system. The quadratic performance criterion or cost function is shown in Eq. 3.

$$J=\int_0^{\infty} \underbrace{\vec{x}^T(t)\cdot Q\cdot \vec{x}(t)}_{\text{Regulation performance term}} + \underbrace{\vec{u}^T(t)\cdot R\cdot \vec{u}(t)dt}_{\text{Control effort term}}$$

solving by

$$\min_{\vec{u}} J(\vec{u}) \Rightarrow \vec{u}\,^*$$

$$\vec{u}\,^* = -K\cdot \vec{x}$$

$\vec{x}$	controlled variables
$\vec{u}$	manipulated variables
Q	weighting matrix
R	weighting matrix

Equation 3. Quadratic performance criterion[4,5]

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The controller properties can be specified by the weighting matrices Q and R. The regulation performance (reaching of the target temperature) and the control effort work oppose each other. The optimal control trend can be changed by the value of the matrices.[5] In the present case, high values of the control effort weighting matrix (R) force the control to reduce the amount of cooling and therewith to increase the temperature homogeneity of the strip.

Goal of solving the algebraic Riccati equation (Eq. 4) is to minimize the Regulation performance term. The result is an optimal gain matrix K. This gain is called the LQ-optimal gain.

$$A^T P + PA - PBR^{-1}B^T P + Q = 0$$
$$u^* = -K \cdot x = -R^{-1}B^T P \cdot x$$

A	system matrix
P	solution of the Riccati equation
B	controlling matrix
R	weighting matrix
Q	weighting matrix
K	LQ-gain matrix

Equation 4. Algebraic Riccati equation

The calculated closed-loop optimal gain matrix (K) leads to an exponentially degressive operating point curve of the cooling track. Fig. 4 shows the calculated graph for a cooling track of 1.5 m, a strip thickness of 2 mm at a velocity of 0.5 m/s, with an initial temperature of 1000 °C, a desired discharge temperature of 500 °C and a three times higher emphasis of regulation performance towards control effort. The result is the optimal trend of the heat-transfer coefficients (i.e. heat evacuation) that the strip has to receive as a function of time. It can be transformed into a function of place depending on the velocity of the strip. Thereby, the positions of the heat evacuation values which have to be rendered by the cooling track can be nearly considered by the control. The control unit can not change the heat transfer value in an infinitesimal small way. That is the reason why the cooling track is separated into several independent sections. A further advantage of this segmentation is the versatility. As each section is controlled separately, it gets easier to change parameters in the process control. Especially for testing purposes it is very easy to change the behaviour of each section of the cooling track.

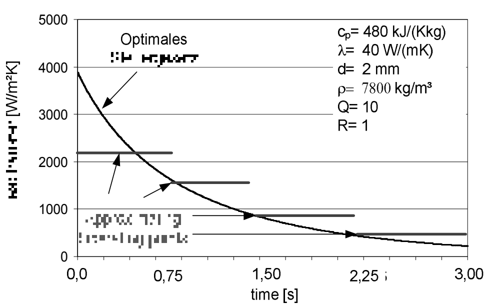

Figure 4. Open-loop operating points of each section of the cooling track.

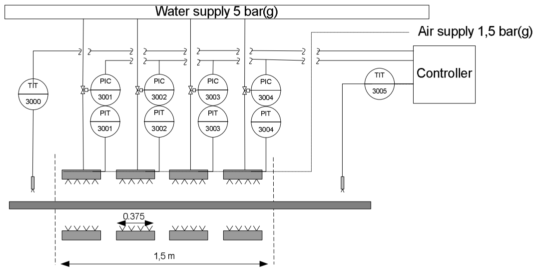

Figure 5. Cooling track schema.

2.3 Construction

The mechanical construction of the cooling track goes hand in hand with the development of the control procedure. Each operating point is a mean value of a parameter-specific variant of the graph shown in Fig. 4 within the boundaries of each section. Consequently the segmentation of the cooling track must also be realised in the construction of the cooling device. The resulting heat transfer coefficient value is calculated continuously. In a cooling table it is discretly approximated to the LQ-optimal gain (Fig. 4). The segmentation is necessary and inevitable for the technical assembly. To increase the quality of the cooling track the number of sections has to be increased. This comes along with increasing costs.

The LQ-gain is calculated continuously by the control regarding strip thickness, velocity, initial temperature, the user-defined gain matrices (Q and R) and the desired departing temperature.

For small readjustments of the strip exit temperature a separate superior closed-loop PID temperature controller has been installed. The outlet temperature of the cooling track will be measured. In case of a control difference between setpoint an real value the control will change the cooling settings of the track. The entire cooling track control operates by using a subordinate closed-loop water pressure regulation, utilizing the nozzle-specific heat transfer curve found in Fig. 6 which will be described later. The advantage of an additional pressure regulation loop towards a simple valve-opening based control is its superior reliability.

Due to the originating water steam, it is virtually impossible to measure the strip surface temperature during the cooling process. Therefore, the established cooling model is used as an observer. Since only the surface temperature of the strip after passing through the cooling track can be quantified, this value is taken as a basis to calculate the different layer temperatures inside the strip. Each section of the track has a separate closed-loop control and gets its operating point from the observer (Fig. 4, 5).

2.4 Heat Transfer Coefficient

The cooling track is equipped with two-fluid nozzles. These nozzles possess several advantages compared to conventional ones, i. e:

- More dispersed driblets lead to better heat dissipation and, as a result, to higher efficiency.
- The additional acceleration of the driblets due to air pressure increases cooling by higher impacts.
- Wide adjustment range.

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- Parameter disturbances due to pressure dropouts are less likely to impair the cooling process quality.

All these advantages plead for the use oft two-fluid nozzles. For the cooling track at hand, a jet of the company Spraying Systems (Type: Caster Jet D26867-03900-140720-BR) [6] has been applied. It is a flat spurt nozzle which has a consistent fluid allocation and a wide range of adjustment. In a series of tests with constant air pressure (22 psi), the water pressure was varied (5 - 40 psi) to figure out the relation between water pressure and resulting heat coefficient of the nozzle (Fig. 6).

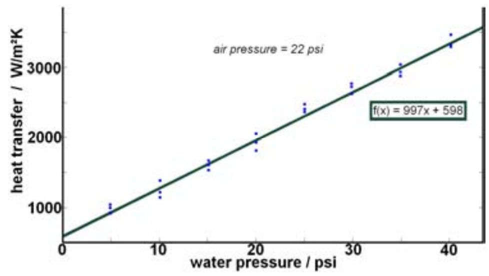

Figure 6. Relation between water pressure and heat transfer coefficient.

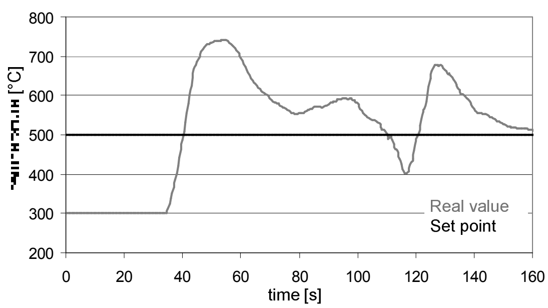

Figure 7. Result graph.

2.5 Installed Cooling Track: Experimental Validation

The simulation of the cooling track is validated by test runs on a laboratory hot-rolling processing line at the Institute for Metal Forming at RWTH Aachen University. The length of the cooling track is 1.5 m and the strip has a velocity of 0.5 m/s with a inlet temperature of 1000 °C. The thickness of the strip is 2 mm. The control system is implemented in PLC S7 from Siemens. The setpoint is 500°C and the real value is shown as the gray curve in the graph Fig. 7. The set point is reached after a transient oscillation time of circa 100 s. The pyrometric measurement during the test was significantly impeded by water steam.

3 BENEFIT FOR STEEL TECHNOLOGY: EXPERIMENTAL VALIDATION

The presented algorithms allow controlled heat treatments including quick cooling cycles. The possible benefit on the material properties is shown by annealing experiments on a laboratory scale with steel sheet. As demonstrators the “Quenching and Partitioning” concept and annealing for repeated bcc-fcc-bcc transformation (cyclic annealing) were chosen. Both approaches require several heating and cooling cycles to precise temperature setpoints.

3.1 Cyclic Annealing: A Concept for Grain Refinement

Grain refinement has proven to be a adequate means to increase simultaneously strength and ductility.[7] The concept of cyclic annealing aims to diminish the ferrite grain diameter by repeated phase transformations from bcc to fcc to bcc phase. The triple points and grain boundaries are preferred nucleation sites for the diffusion controlled phase transition.[8,9] Hence the grain diameter is reduced by a phase transformation if grain growth after the transformation does not occur. Additional nuclei may be delivered by intra-granular dislocations, Fig. 8.

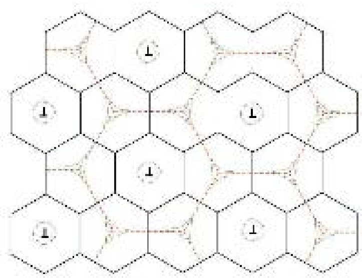

Figure 8. Grain size reduction by phase transition (mother phase: broken lines; nucleation sites: dotted lines, _|_: intra granular dislocation).

The experiments were carried out with two cycles for the sheet steel. Its chemical composition is given in Tab. 1. The tests started with a full austenitization followed by rapid cooling to a lower temperature for bcc transformation. A second heating lead again to a fully austenitic condition for the subsequent controlled cooling to the desired microstructure. The exact design of the annealing cycle was determined in dilatometer tests. For the given conditions, the necessary transformation time was correlated with the transformation temperature, the cooling rate and the microstructure obtained from a micrograph.

Table 1. Chemical composition of sheet steel for cyclic annealing in weigth-%

C	Si	Mn	P	S	N
< 0.2	< 0.50	< 1.50	< 0.002	< 0.001	< 0.020

3.2 Cyclic Annealing: Required Equipment

Generally, the cyclic annealing concept requires devices for the repeated heating and cooling of the steel strip. Important features of the cooling track are first fast cooling rates to limit the time for grain growth at higher temperatures. Dilatometer tests proved a cooling rate of 50 K/s satisfactory. Under these cooling conditions even martensitic transformation has been verified on the installed cooling track (Fig.9c). The final cooling conditions range from 50 K/s to 10 K/s allowing for a large variety of final microstructures.

3.3 Cyclic Annealing: Effect on Microstructure and Mechanical Properties

The possible ferrite grain refinement is obvious from the micrographs displayed in Fig. 9 a-c. The minimal value of the grain diameter is below 5 µm. Additionally to the reduced grain size, the cyclic annealing approach allows the controlled adjustment of

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the microstructure, e. g. a dual phase (DP) steel with martensite in a ferritic matrix (Fig. 9c). As expected, the reduced grain size is accompanied by an increase in strength and ductility, presented for ferritic microstructures in Fig. 9d.

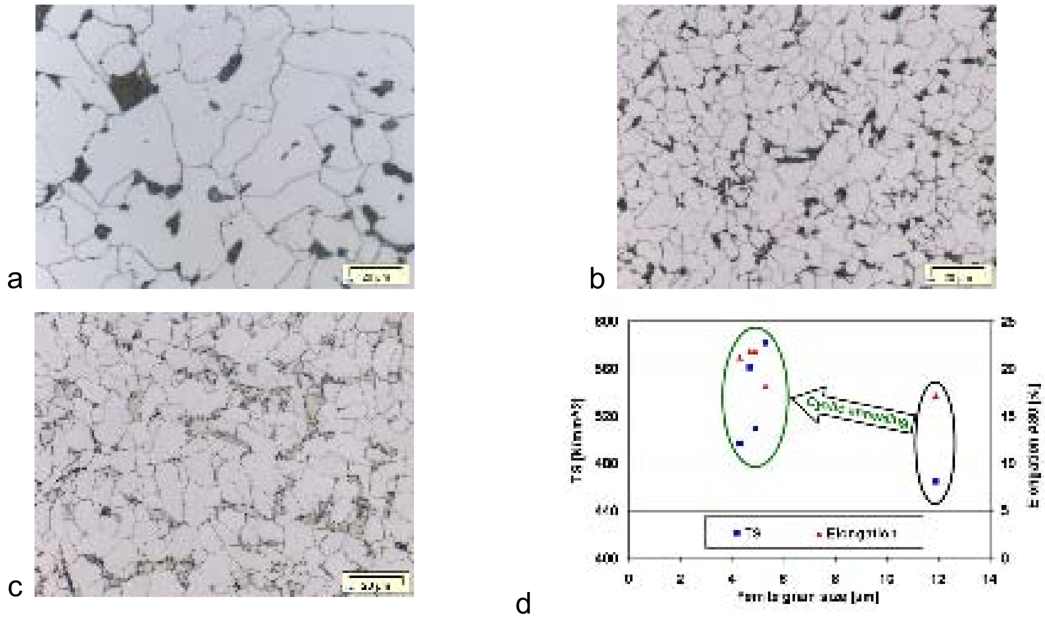

Figure 9. Cyclic annealing: microstructures and mechanical properties: a initial, coarse ferrite-pearlite; b grain refined ferrite-pearlite; c DP microstructure d mechanical properties before/after cyclic annealing.

3.4 "Quenching and Partitioning": An Innovative Heat Treatment Concept

A heat treatment process named "Quenching and Partitioning" (Q&P) has been published in 2003 for the production of steel with improved mechanical properties. In a first step the steel is completely austenitized and then quenched to QT (quench temperature). As QT lies below martensite-start M_s but above -finish M_f, a part of the austenite transforms to martensite. The second so-called partitioning step at a slightly increased temperature allows carbon atoms to diffuse from martensite to the temporary austenite. Thus its M_s temperature decreases under room temperature giving stability on the concluding quenching.[11-15] Fig. 10 shows a schema of the process and the resulting microstructural features.

The alloying concept of Q&P steel corresponds to the heat treatment. A typical composition for sheet steel is presented in Tab. 2. A threshold of 0.200 % carbon is set due to the demand of posterior welding operations. Manganese acts as solid solution strengthener and facilitates the martensitic transformation. Silicon plays an important role in TRIP-assisted steels as it impedes the formation of carbon precipitates.[16] Carbide precipitation is not accepted for Q&P because carbon is chemically bound and hence missing for the chemical stabilization of temporary austenite.

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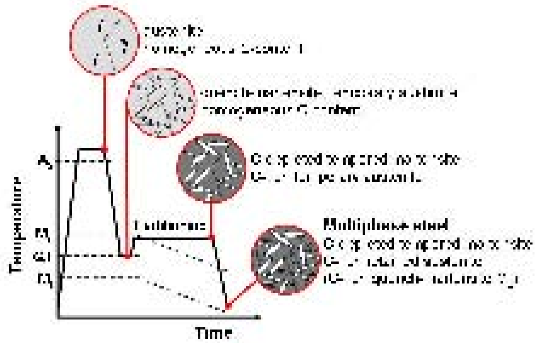

Figure 10. "Quenching-and-Partitioning": schema of heat treatment and microstructure.

Table 2. Q&P sheet steel, chemical composition in weight-%

	C	Mn	Si	Al
Si alloyed	< 0.200	< 5.00	< 2.00	-
[17]	0.190	1.59	1.63	0,04

3.5 Q&P: Effect on Microstructure and Mechanical Properties

By choosing the quenching temperature QT and the subsequent partitioning temperature / time the tensile strength and the elongation can be varied in a broad range. Fig. 11 gives an example for the dependency of mechanical properties on QT for a given partitioning temperature for 10 s and 30 s, respectively. The microstructure consisted of tempered martensite with retained austenite. The data for a QT of 220 °C were taken from.[17] The austenite volume content measured with X-ray diffraction was well below 10.0 %.

A clear decrease of the tensile strength is visible for increasing QT. The elongation values increase correspondingly though showing a plateau for the higher QTs. For a QT of 300 °C a tensile strength above 1100 N/mm^2 is achievable at a total elongation above 11 %. This combination is interesting for an industrial application where high formability and strength are as well expected as a robust process to adjust these properties.

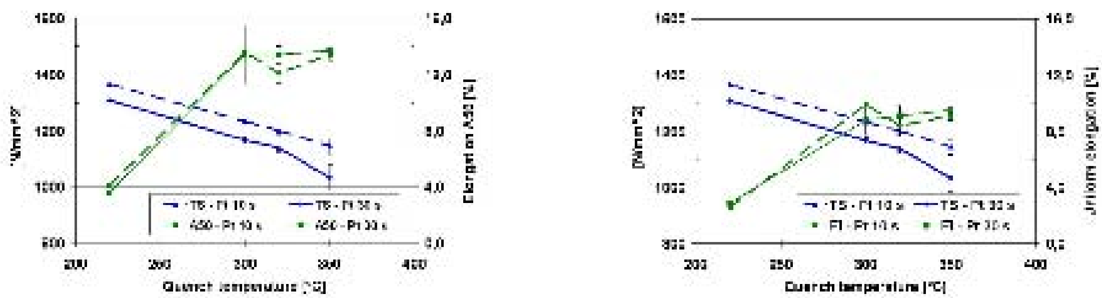

Figure 11. Dependecy of tensile strength (TS), total (A50) and uniform (El) elongation on quench temperature. The data for 220 °C was taken from.[17]

3.6 Q&P Heat Treatment: Required Equipment

In general the Q&P process requires devices for heating into the austenite region, for intermediate quenching, for reheating to the partitioning temperature and ultimate cooling. The austenitization temperatures are up to 1000 °C while

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intermediate quenching is to temperatures of 300 °C ± 150° C. The exact temperatures depend on the alloy and the corresponding transformation temperatures. Partitioning temperatures above 450 °C are to be avoided because the tendency for carbide formation becomes pronounced. Another competing reaction to Q&P is the isothermal bainite formation at the partitioning temperature. It would consume temporary austenite and consequently reduce the possible amount of retained austenite to be used for the TRIP effect.

The necessary temperature rates for Q&P were measured in a dilatometer of type DIL 805 A/D, Baehr Thermoanalyse. It records the change of the length signal and the corresponding temperatures as a function of time. The martensitic transformation on quenching is detectable as well as isothermal bainitic transformations. In Fig. 12 results of two dilatometer experiments are displayed. The left pair of curves was measured during Q&P processing. The right pair is a record of an isothermal bainite transformation at the partitioning temperature used for Q&P. Note that for displaying reasons the time scale of the bainite curve was shifted to longer times (+ 150 s). During the first quenching of Q&P the length signal indicates clearly the martensite transformation (Fig. 12-1). During the following heating and partitioning (Fig. 12-2) only a slight change of the length signal is observed under the given temperature conditions. In contrast no martensite transformation is indicated during the quenching to the bainite transformation temperature (Fig. 12-3). Once on the transformation temperature the length signal shows the characteristic sigmoidal development (Fig. 12-4) accorded to the bainite formation. The isothermal transformation is hence excluded for the displayed Q&P parameters using a quenching rate of 50 K/s for intermediate and final quenching.

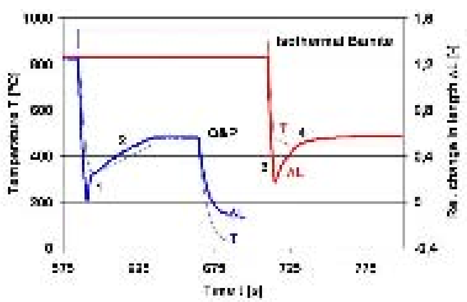

Figure 12. Comparison of Q&P process and isothermal bainite transformation.

3.7 Flexibility of Cooling Conditions and Homogeneity of Cooled Strip

In strip steel production the cooling track is decisive for both the attainable variety of the property suited microstructures and of its distribution throughout the length and width of the produced strip. Therefore the performance of the cooling track realised in line with the one-stand laboratory scale hot rolling mill was characterised. Sheet steel of the chemical composition given in Tab. 1 (*Si alloyed*) was hot rolled and subsequently cooled to a martensitic-bainitic and a ferritic-pearlitic microstructure. Along the length and width of the strip, micrographs were taken and the hardness was tested, Fig. 13.

Over the width (side a - b) a very good homogeneity is observed. The comparison of head and foot of the strip also shows a good correlation. Some deviations may arise from the different cooling conditions on the coiler installed after the cooling track. As a characteristic of the laboratory set up the first turns on the coil

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cannot be cooled. Thus the later windings are annealed resulting in a metallographically not detectable difference between annealed martensite and bainite. Nevertheless the cooling track is efficient in promoting the diffusionless phase transformation in the investigated TRIP-assisted steel grade.

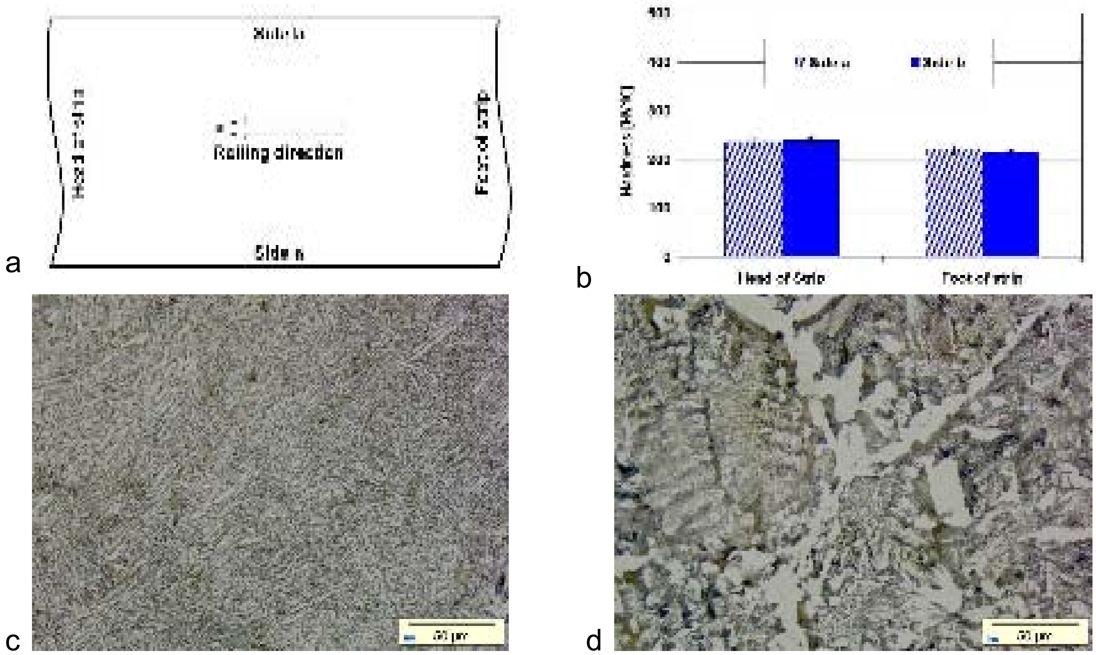

Figure 13. A sampling of steel strip; b homogenious hardness distribution in martensitic-bainitic microstructure; example microstructures (Nital etching 500:1): c bainite / d ferrite-pearlite.

4 CONCLUSIONS

The described algorithms for the control of a water-cooling track in line with a one-stand hot rolling process line uses a Linear-quadratic Gaussian Method. It assures the accurate regulation and monitoring of the temperature of steel strip during innovative heat treatments. The necessary modular setup of the cooling track in separately controlled sections increases the process flexibility. The feasibility of presented approach was proven. Its possible application on state-of-the-art heat treatments of multiphase steel was demonstrated for the “Quenching and partitioning” process and grain refinement by cyclic annealing.

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