NEW TECHNOLOGIES
for manufacture of thin high-strength hot and cold strip

METALLURGICAL PLANTS and **ROLLING MILL TECHNOLOGY**

HOT and **COLD STRIP MILLS**

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Developments in materials and rolling technology

Since the late 80s the product spectrum of hot strip mills has radically changed. For one thing the soft steel grades are being rolled with end gauges of 1 mm and for another thing the steel industry has developed high- strength materials (e.g. C95; CP1000; S700M) that are required in thin end dimensions (h ≤ 2,1 mm).

Apart from the higher demands with regard to the strip quality such as gauge and flatness tolerances, surface structure and mechanical properties for the direct processing of hot strip (e.g. rim steels), it is very difficult to roll these qualities in a hot strip mill with a low disturbance rate due to the great complexity of the materials.

Rolling stability, which influences the productivity (disturbance rate) and product quality to a great degree, is defined essentially by the following criteria:

- Stability with regard to material behaviour (recrystallisation) within the hot strip mill, in particular with highly Nb-alloyed materials.
- Stability with regard to the threading-in and -out procedures.
- Stability with regard to the strip flow (interstand flatness parabolical or linear).

Thanks to the use of newly developed technologies rolling stability has been increased far enough for the materials described above to be manufactured with a high productivity and product quality. Furthermore, scope is being created for future material developments as well as for other strip dimensions (enlargement of the strip width, reduction of the strip gauge).

New technologies have been developed for the cold rolling process due to the fact that high-strength materials are often rolled cold. This enables rolling stability to be increased and the strong thermal and mechanical strain on the plants because of the material properties to be reduced. Here as well the increased demands with regard to product quality will have to be met.

Material development using the example of the automotive industry

Since the beginning of the 90s the use of innovative material concepts in the car industry has constantly been increasing. An essential contribution to this has been made by a growing environmental consciousness of the need to reduce the consumption of fuel. Furthermore, the requirements for greater passive safety have led to the new materials being designed in a particularly energy-absorbing way. Thanks to the new steel grades car bodies with a considerably reduced weight have been created with a simultaneous increase of the safety standard.

Steel possesses by far the greatest development potential compared with other materials in respect of light-weight designs. While prior to 1990 the share of conventional steels in car building amounted to ca. 65 % (**Figure 1**), the share of higher-strength steels from this date onwards has constantly risen. According to forecasts it will be more than 42 % in 2005.

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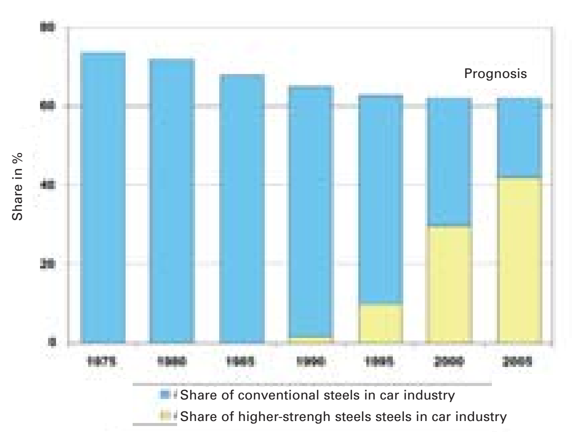


Figure1: Share of conventional and higher-strength steel grades in car industry.

With the new steels greater elongation values and the improved cold deformation properties resulting therefrom can be achieved in comparison with conventional materials of similar strengths. **Figure 2** shows a comparison in this connection of the properties of conventional and newer higher-strength steel grades [1 – 3].

IF (interstitial-free) steels are suited due to their excellent cold deformation capacity both for the highest deep-drawing and stretch-forming stresses in the lower strength range. These very deeply carbonised steels undergo a complete binding of the interstitially dissolved elements carbon and nitrogen by microalloying with titan and/or niobium.

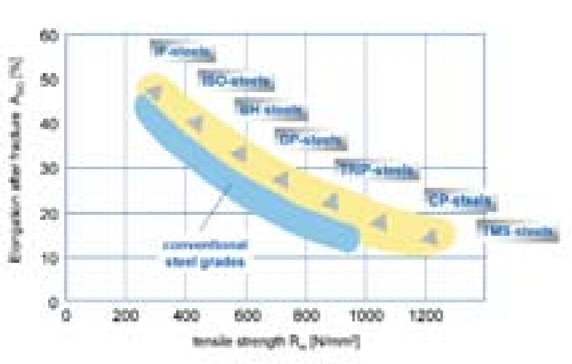


Figure 2: Properties and application of conventional and new steel grades.

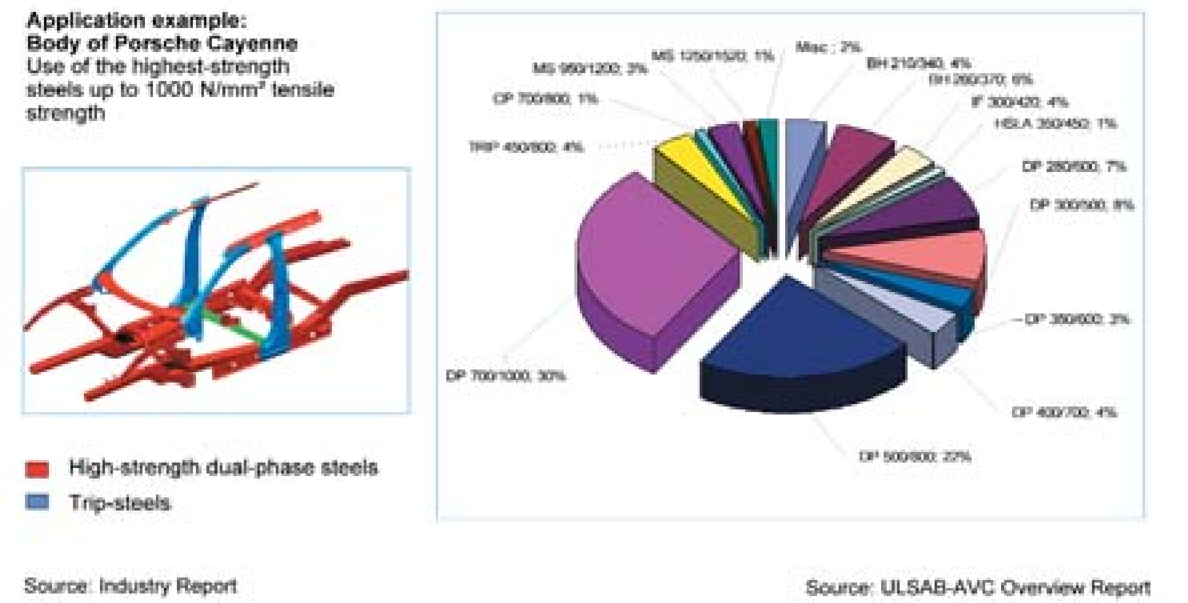
A special form of strength incrementation is obtained in "bake-hardening" (BH) steel. A yield point increase is produced during the paint enamelling treatment by the diffusion of carbon in dislocations of the ready-deformed components.

With multiphase (DP, Trip, CP) steels the increase in strength is achieved by hard phases being introduced into the microstructure in addition to soft phases. With complex-phase steels tensile strengths of up to 1000 MPa are thus attained. The microstructure is very fine-grain with a homogeneous distribution of microdispersions. Strengths in the range from 1200 - 1400 MPa can be achieved by the martensite-phase steels (TMS).

Figure 3 shows the use of high-strength dual-phase and Trip steels with the example of the body of the Porsche Cayenne. The components (blue) most affected by a side crash consist of Trip steel, in which the rest austenite transforms into martensite as a result of the deformation in the manufacture of the body component. The material thus undergoes a strength increase. Furthermore, Figure 3 shows the percentage break-down of the various higher-strength steel grades in the automotive sector. The yield point and the tensile strength are indicated in addition to the steel grade in each case.

The properties and application possibilities of selected microalloyed steels are shown in **Figure 4.** A distinction is made here in accordance with the type of the microstructure generation (rolling or cooling process).

The materials QE500 and S700M are characterised by a fine-grained ferritic-perlitic microstructure. The QE500 can be rolled both in a normalising and thermomechanical way. In contrast, the S700M is rolled thermal-mechanically. With these two steels the microstructure is essentially formed by the rolling process. As the result of a controlled progression of the temperature during rolling there is a strength increase by the formation of finely distributed precipitations (nitrides, carbonitrides).



Source: Industry Report

Source: ULSAB-AVC Overview Report

Figure 3: Share of the various steel grades in the automotive sector.

In contrast, the microstructure-formation process with the multiphase steels (DP and CP) is performed by the cooling process after rolling. The DP-steel possesses a ferritic-martensitic microstructure. The CP-steel is characterized by a fine-grained ferritic-bainitic-martensitic microstructure. With both materials the yield point can be further increased by paint enamelling procedures.

Steel type	Microstructure creation by rolling process	Re/Rm. N/mm²
QE500 Mn-Nb-Ti-steel	Good weldability, good deformability, QE-qualities for direct processing or for cold rolling, use in car building (sidewalls, wheels)	400/500
S700M Mn-V-Mo-Ti-Nb-steel	Especially suitable in crane building, e.g. safety elements (similar to **U**ltra **F**ine **G**rain)	720/820
	Microstructure creation by cooling process	
Dual phase steel, TM-rolled, (DP-W)	Good cold deformability, strain hardening with low starting yield point, use e.g. for wheel disks, body reinforcements	330/580
Complex phase steel, microalloyed, (CP-W)	Relatively good cold deformability and weldability high strength and resistance to wear, relatively high strain hardening, use e.g. for door crash carriers, bumpers, crash-relevant parts	680/800 700/880 720/950

Figure 4: Selected examples of hot-rolled highly microalloyed steels and multiphase steels.

Hot rolling technology for manufacture of high-strength materials

Figure 5 shows the most important technological modules for the hot rolling of high strength materials. These great dependencies of the individual sub-processes upon each other lead to a manufacturing process of high complexity. These correlations will be explained below.

The material- as well as the strain hardening and -softening models deliver the material characteristics for the pass-schedule model. In the first iteration stage the typical process variables (reduction distribution, temperature) are calculated for example for rolling in a finishing train with the aid of the pass schedule. If a stable recrystallisation behaviour is not given or the process variables reach their limit, a stable pass-schedule is made iteratively.

This pass schedule is passed on to the profile and flatness model and a check is made whether rolling is possible on the basis of the stability criterion "interstand flatness". If this criterion is fulfilled, the setup data are passed on by the control systems, otherwise a new pass schedule is generated.

Apart from the usual setup data for the finishing train (rolling force, gauge and speed) the control systems, in particular the gauge and mass-flow controls, require adaptive controller settings that are calculated in every rolling pass for each mill stand due to the considerable change of the individual gradients ($\partial Fw/\partial h$; $\partial Fw/\partial kf$; $\partial Fw/\partial \sigma$;Fw = rolling force, h = strip gauge, kf = deformation resistance, σ = entry/delivery tension) of the various materials. If it becomes clear during rolling that the unflatness in the interstand area increases too much, the load distribution is dynamically changed by the gauge control system, in particular on finishing trains without profile actuators. The strip flatness is then improved to such a degree that stable rolling is ensured.

Four of the technology modules shown in **Figure 5** will be described in detail below.

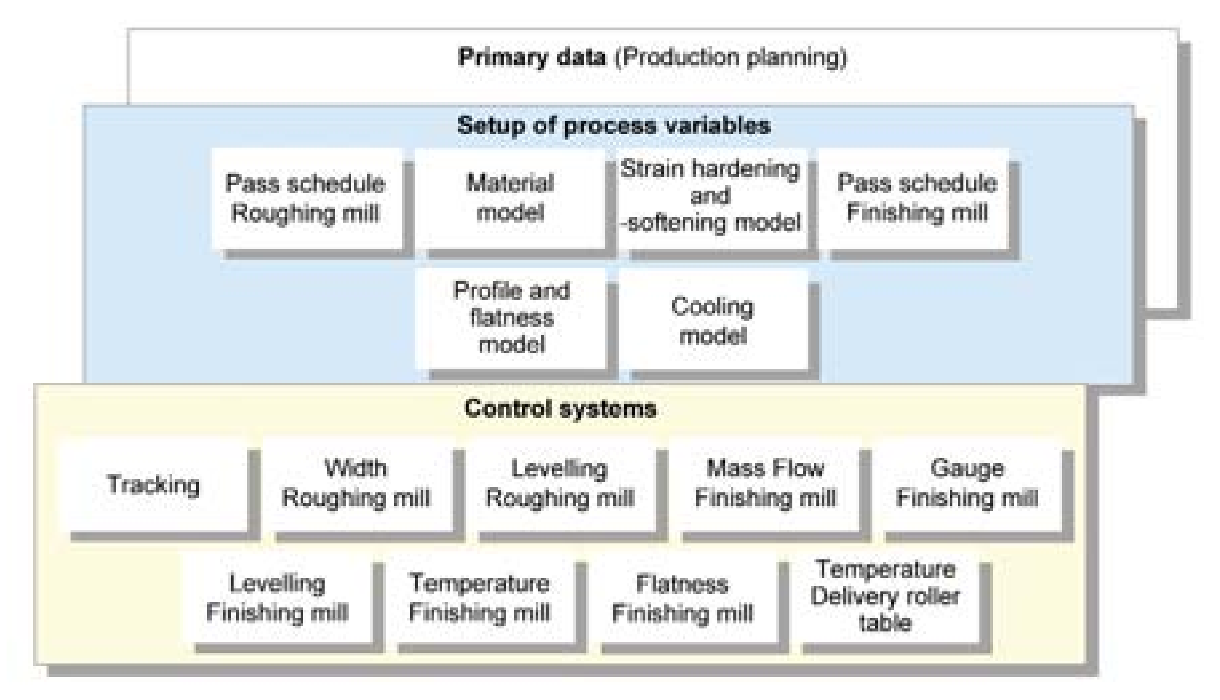


Figure 5: Selected modules of the technological concept for the manufacture of high-strength materials for deep-drawing in hot strip mill.

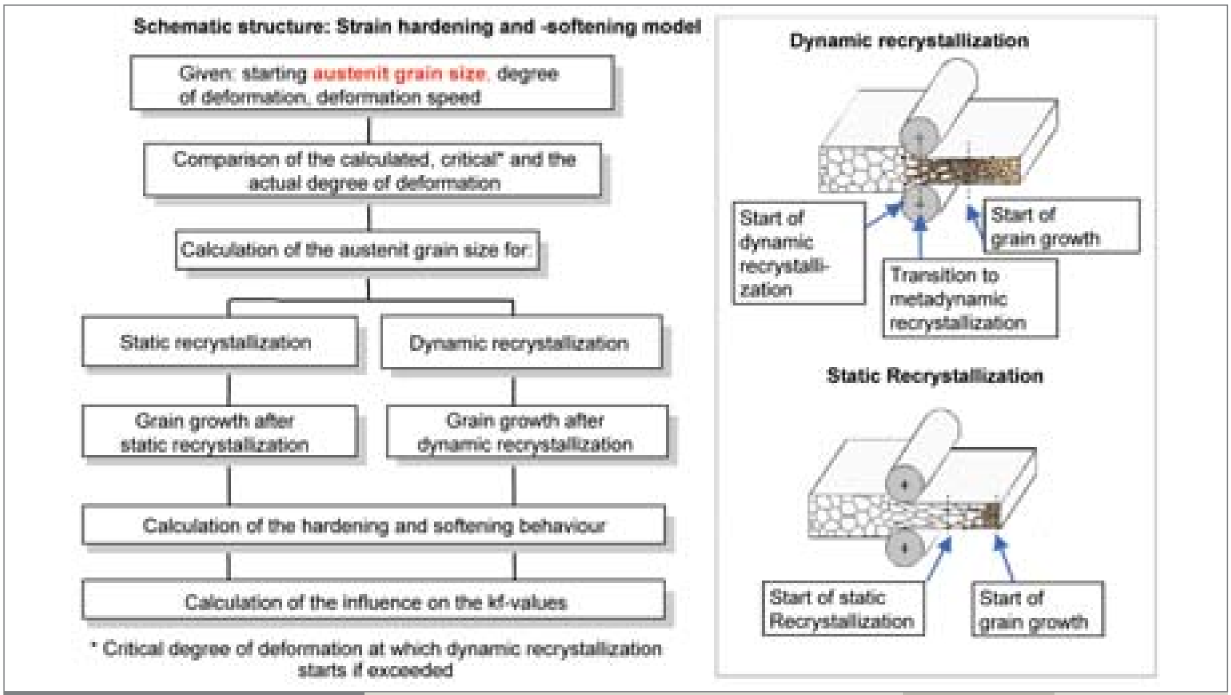


Figure 6: Structure of strain hardening and softening model.

Strain hardening and softening model

On conventional hot strip mills the material behaviour of microalloyed materials is very difficult to control due to the large temperature differences between the head and tail end of the strip as well as to the speedup that thereby becomes necessary at low end rolling temperatures and small end gauges. The reduction distribution (split of the gauge reduction between individual mill stands) has proved to be an actuator for the influencing of the material properties and especially of the recrystallisation behaviour of the material. It may happen with a reduction distribution that is not optimal that 3/4 of the strip can be rolled in a stable manner and then uncontrolled recrystallisation procedures occur.

This phenomenon originates in different recrystallisation behaviours caused by temperature both along the strip length and across its width. This means that across the width (caused by slight temperature differences of $\Delta T \approx 25$ °C) the fast dynamic and the slow static recrystallisation may occur at the same time, which leads very quickly to rolling instabilities (cobble).

If a stable rolling process is to be ensured, this means that the static recrystallisation, which requires an incubation period for the formation of new grain after deformation, and the dynamic recrystallisation, in which the formation of new grain takes place direct during deformation, above all have to be taken into account. **Figure 6** shows schematically the structure of the model for the calculation of the physical procedures described above.

The typical strain hardening and -softening behaviour during the finish rolling of a highly microalloyed material is shown in **Figure 7**. It can be seen clearly that the material runs into stand F3 along the complete strip length fully strain softened. From this stand onwards no more dynamic recrystallisation takes place and there is just a small static strain softening in conjunction with a constant increase of the overall strain hardening. The repercussions of the strain hardening and softening upon the kf-values are shown in the bottom part of Figure 7. The rolling process can be regarded in this example as stable.

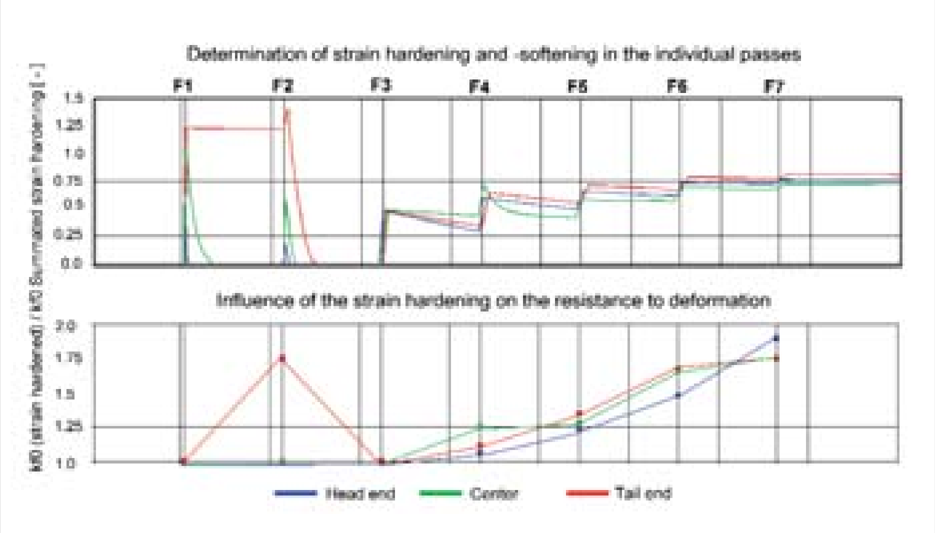


Figure 7: Strain hardening and -softening of highly microalloyed Nb-steels, rolled thermomechanically.

Profile-, contour- and flatness model

When rolling high-strength materials a stable strip flow above all must be ensured as already described. In order to ensure that this is the case, the expected process variables must be determined with a high degree of accuracy. The physical model that calculates these variables is shown with the essential constituent parts, i.e., roll condition, roll deformation and material model in **Figure 8.** The strip profiles and flatnesses as well as the settings of the profile final control elements are calculated for all mill stands iteratively with the profile actuators under varying boundary conditions (rolling programme structure, transfer bar profile, strip drawing times, mill stand loads, backup roll condition etc.).

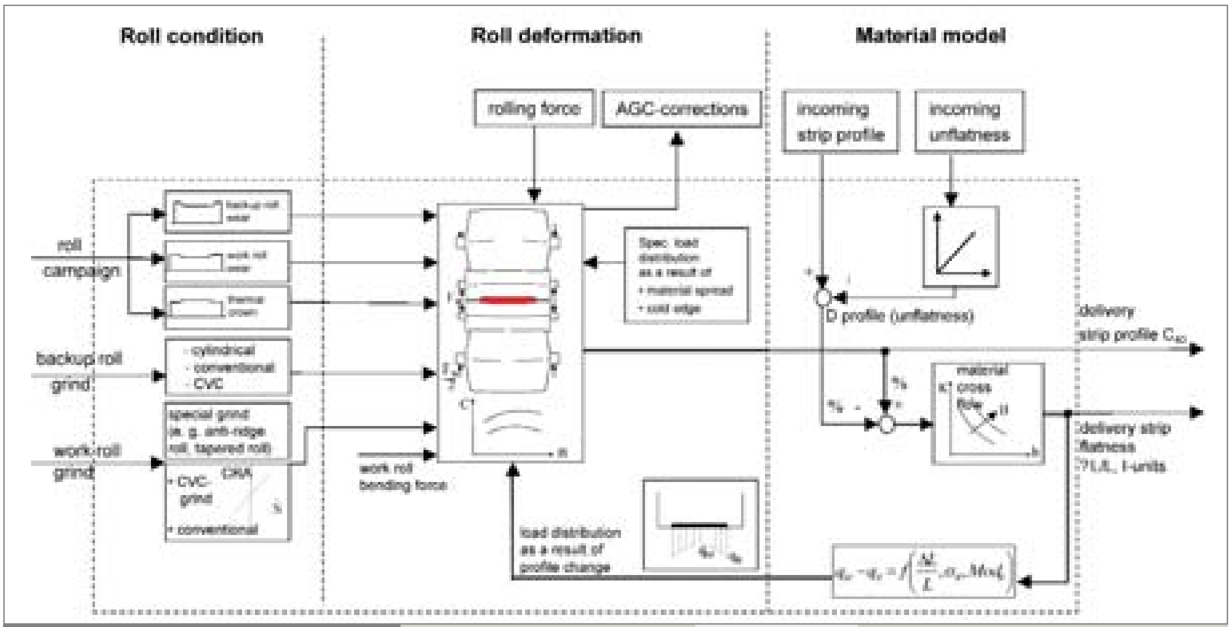


Figure 8: Essential functions of profile, contour and flatness model.

When rolling soft to medium-hard material grades the material may flow in the length direction due to the low kf-values in the interstand area with a corresponding tensile stress. Roll gap errors (unflatness) therefore have no repercussions.

When rolling high-strength material grades no flow takes place in the interstand area. Relative parabolical errors in the roll gap of ca. 3 - 5 µm lead in the delivery-end stands to overrolling due to the summation of the flatness error and thus direct to a failure of the rolling process.

When rolling these materials large dynamic changes of the process variables (rolling force, thermal crown of the rolls) also occur along the strip length. These are measured and compensated by the model by using the work roll bending system. The result is that the flatness state along the strip length is kept constant and symmetrical strip breaks and overrolling at the tail end of the strip are minimised.

Furthermore, narrower tolerances are being demanded by the processing industry, in particular for slit products (Ck67, 58CV4, HR60, QE460). With the newly developed models and control systems strip profiles of 40 µm can be manufactured in a stable manner today in narrow tolerances for high-strength qualities in strip thicknesses ≤ 2.1 mm, although suitable profile actuators must be available above all in the first stands of the finishing mill to achieve the product quality.

Automatic levelling

When rolling high-strength thin materials, particular importance must be attached to the levelling of the mill stands in the finishing train. As it is shown in **Figure 9,** a non-uniform distribution of the strip tension when threading out of the finishing train leads to a con-siderable run-off center drift of the tail end, in conjunction with breaks. These breaks frequently lead to roll damage and thus to a termination of the roll campaign. The rolling of surface-critical materials for direct further processing (for example HR60 for car rims) in particular is affected thereby.

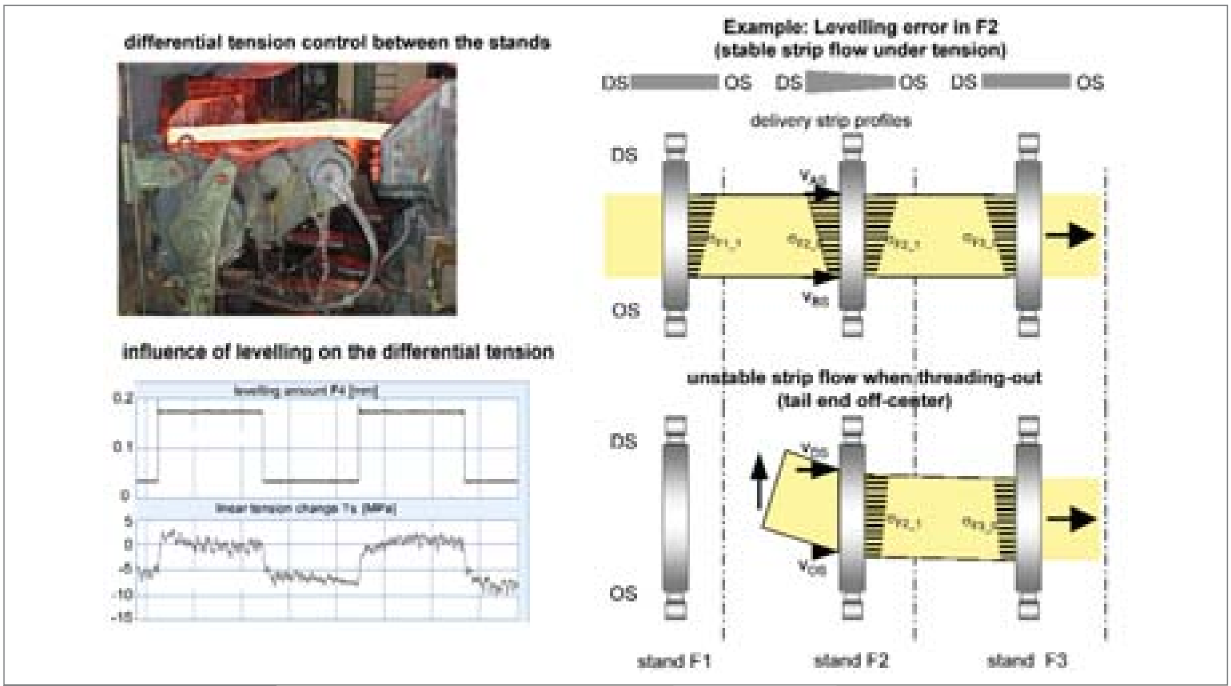


Figure 9: Strip flow stability in hot rolling.

For this reason new measuring and control systems have been developed in recent years for the levelling of the finishing trains in order to increase rolling stability with regard to "symmetrical strip flow". Two different looper measuring systems that are in a position to determine the strip tension distribution during rolling are being used. The differential tension looper determines just the linear part of the strip tension and the tensiometer looper measures both the linear and the parabolical portions.

These measurements serve as a basis for the automatic levelling control of the mill stands in the finishing train. The high accuracy demands both upon the measuring and on the control systems must be fulfilled. Levelling errors of ± 20 µm, related to the roll gap, lead direct to the instabilities described above.

Operating results

To conclude, the operating results of the rolling of material S650M with strip dimensions of 2.0 mm x 1300 mm are shown in **Figure 10.** This rolling was performed on a conventional 7-stand hot strip mill. If in future thinner and even harder materials are rolled, the plant concepts of the mills will have to be adapted to these new requirements by corresponding modernisations.

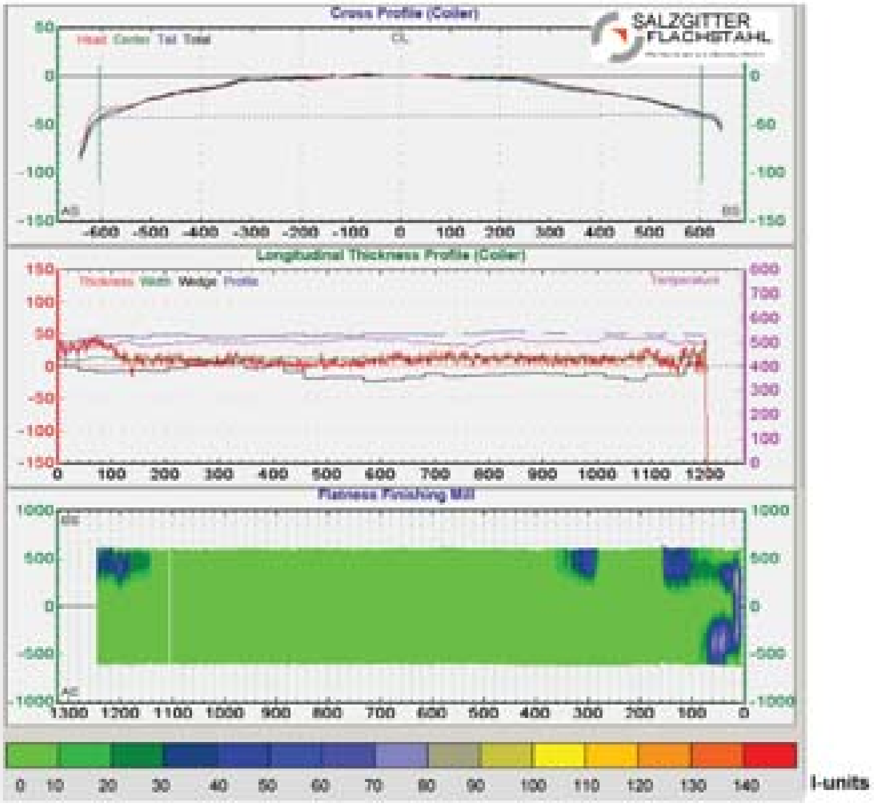


Figure 10: Thermomechanical rolling of Mn-V-Mo-Ti-Nb steels S650M.

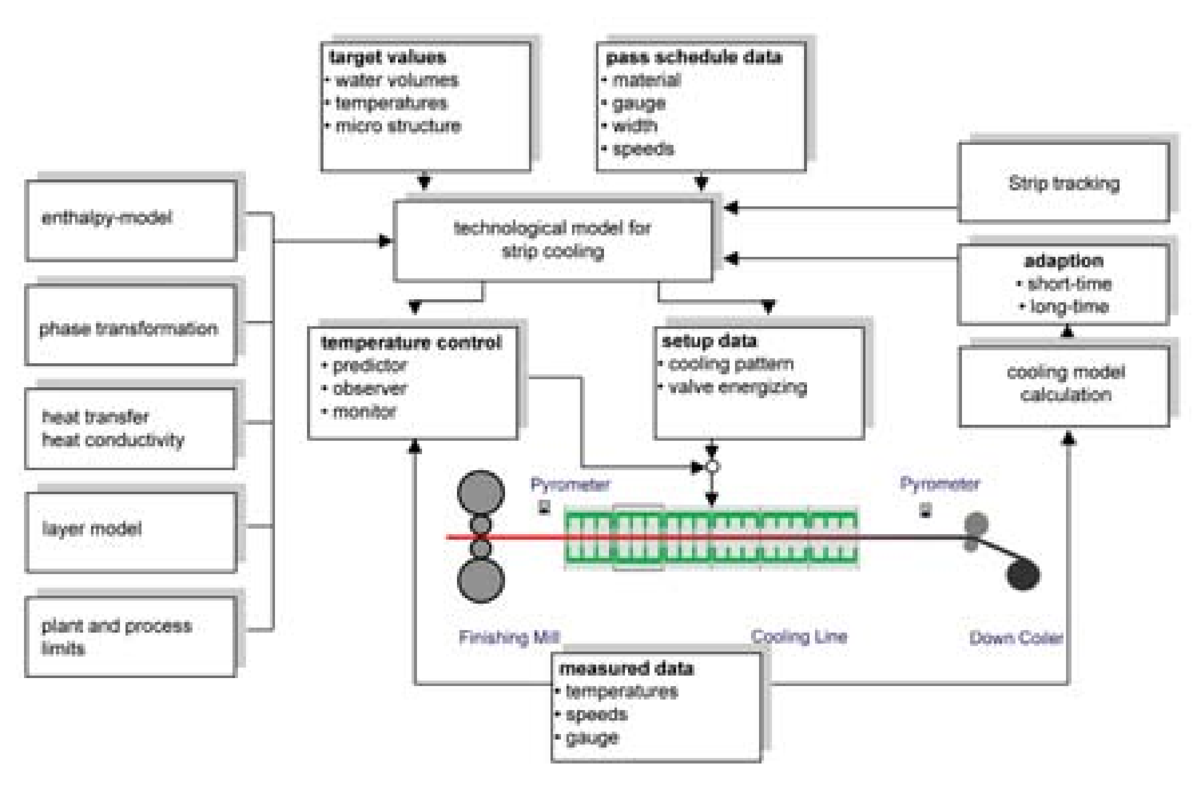


Figure 11: Essential structure of strip cooling model.

Strip cooling

The setting of the mechanical properties of hot strip requires the observation of narrow temperature tolerances. For this reason great importance attaches to the temperature control in the rolling process and in the cooling section.

The coiling temperature can be set with the aid of the cooling model. The essential structure is shown in **Figure 11.** The cooling model takes into account the physical principles of heat transfer and of phase transformation. Control concepts ensure, in the case of a change of the process variables, an almost constant coiling temperature. The setup and control are supported by adaptation and optimisation models in online and offline operation.

The procedures of the heat transfer are described by the physical mechanisms of the convection and radiation on the surface and of the heat conduction inside of the strip. The strip is divided into different layer thicknesses. The number of the generated layer thicknesses depends on the current strip gauge. These procedures can be formulated by the differential equation of the non-steady heat conductions while taking into account thermal boundary conditions. The energy released of the γ-α phase transformation is included as an energy term in the differential equation, whose solution is solved numerically with the finite-difference procedure.

The phase transformation is described using the Johnson-Mehl-Avrami law. Starting from the empirically calculated temperatures for the beginning and the end of the transformation as a function of the chemical composition and of the cooling rate, it is possible at all times to calculate the share of the transformed austenite and to ascertain the energy released.

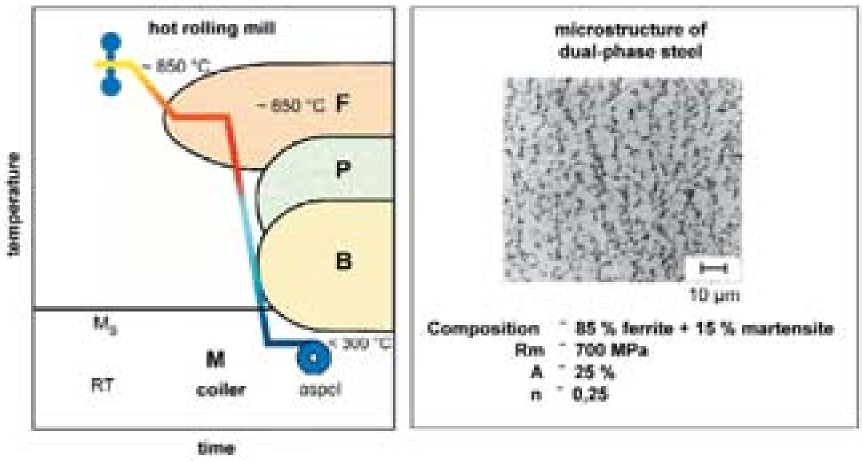


Figure 12: Cooling and microstructure of dual-phase steel.

The cooling of a dual-phase steel is shown in **Figure 12.** Remarkable is the fact that the exact microstructure setting of this material has to be performed at rolling temperatures of up to 11 m/sec. In the event of slight fluctuations of the microstructure portions (martensite, ferrite) the material immediately shows other mechanical properties, so that high accuracy demands both upon the set-up model and on the temperature control exist.

Cold rolling technology for production of high-strength materials

A modelling of the cold rolling process on a physical basis requires an understanding of the interaction of the mechanical, thermal and tribological (that means friction and lubrication) parameters in the roll gap, **Figure 13.** Apart from the yield stress of the material, the coefficient of friction *μ* in the roll gap is an impor-

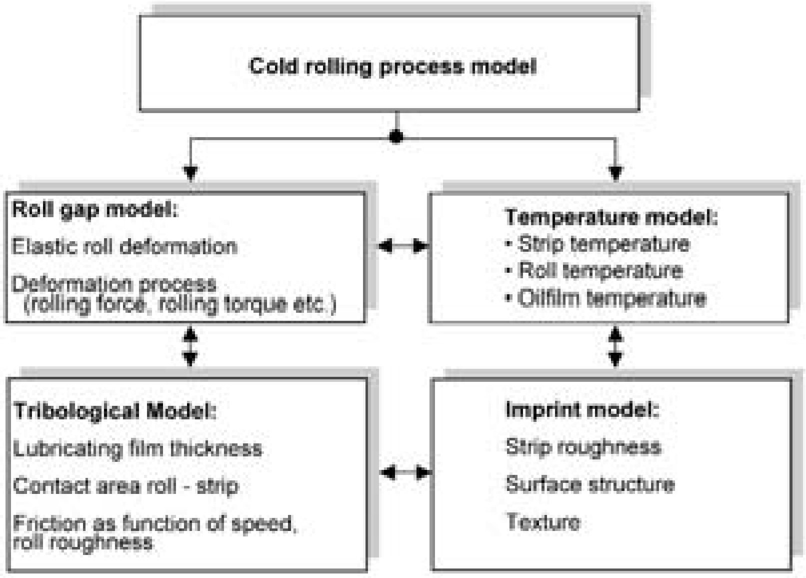


Figure 13: Essential constituent parts of cold rolling process model.

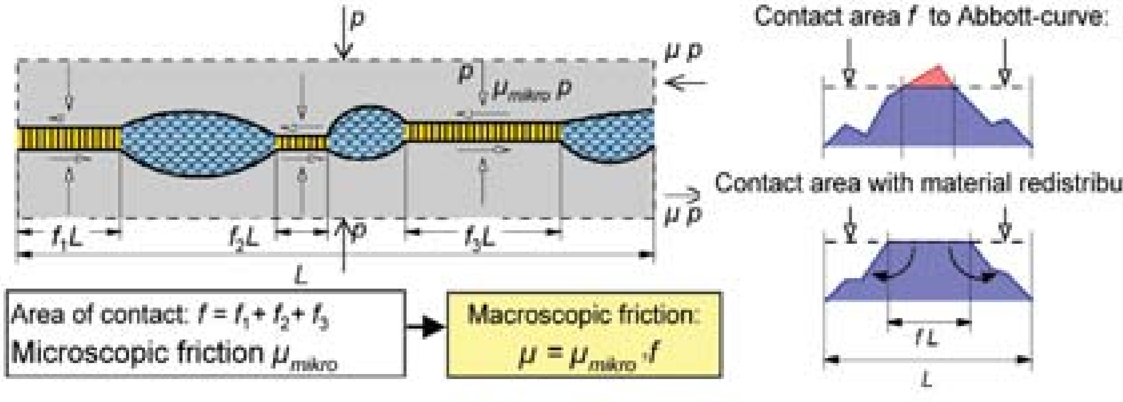


Figure 14: Determination of the fractional area of contact f and of the macroscopic frictions in cold rolling.

tant boundary condition for all roll-gap models. A constant coefficient of friction in the roll gap calculated by empirical values is used in general modelling practice. It is assumed that this value only depends upon the rolling speed. In many cases the use of these assumptions does not sufficiently describe the measured process data.

For this reason a start was made some years ago on the development of a tribological model for the roll gap that calculates the progression of the coefficient of friction μ in the roll gap, the thickness of the lubricant film in the roll gap as well as the transfer of the roughness from the work roll onto the strip. Apart from the dependency upon the rolling speed, it also takes into account other parameters that are important for the roll gap lubrication such as for example the type and composition of the lubricant, the roughness of the rolls and of the strip, the thickness of the oil film on the strip and general pass-schedule parameters such as the strip gauge, the strip tensions, the yield stress, the reduction, the work roll diameter and the temperature.

There is a direct interaction between the tribological model and the mechanical and thermal process model. This enables a more exact forecast of the global process data (the most important are force, torque, forward slip), which are required for a realistic pass-schedule calculation or for an optimal process control.

Cold rolling normally takes place in the mixed-friction range [4 - 6]. The work roll and the strip surface are partly separated by lubricant pockets. The part of the direct contact of the surface roughness peaks is described as the fractional area of contact *f*, **Figure 14.**

In the tribological model the microscopic coefficient of friction μ_{micro} is used for the description of this condition of limit lubrication. It depends purely on the material and on the type of lubricants. The relation to the macroscopically perceivable coefficient of friction is then given by: $\mu = \mu_{micro} \cdot f$. As μmicro is a constant parameter for a particular application, all the other dependencies are only included in the variation of *f*.

The greater the average thickness h_L of the lubricant film in comparison with the average roughness, the smaller is *f*, as also is the coefficient of friction μ in the roll gap. The lubricant film thickness in the roll gap is described by the Reynolds differential equation. An explicit solution exists [4 - 6] for ideally smooth surfaces.

$$h_L = \frac{3\eta_0 \alpha_p (v_R + v_S)}{\alpha \cdot (1 - e^{-\alpha_p p_E})} \; .$$

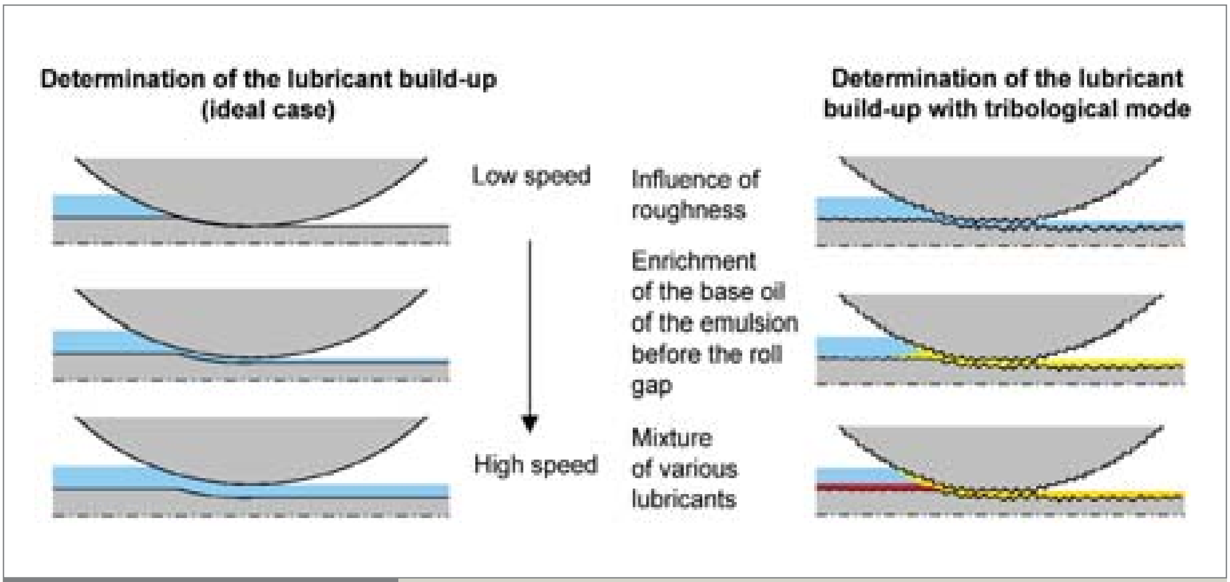


Figure 15: Lubricant build-up when cold rolling from the ideal case of aquaplaning to complex tribological model.

η_0 is the viscosity at room pressure, the coefficient ap takes into account the exponential increase of the viscosity with the pressure, v_R and v_S are the speed of the work roll and of the strip surface, α is the angle of bite, while p_E reflects the pressure at the start of the roll gap. The lubricant film thickness increases in linear fashion with the speed (aquaplaning effect), **Figure 15.** For the realistic modelling the effects of the surface roughness [7] and the enrichment of the base oil of the emulsion before the roll gap were taken into account, so that the Reynolds differential equation has to be solved numerically.

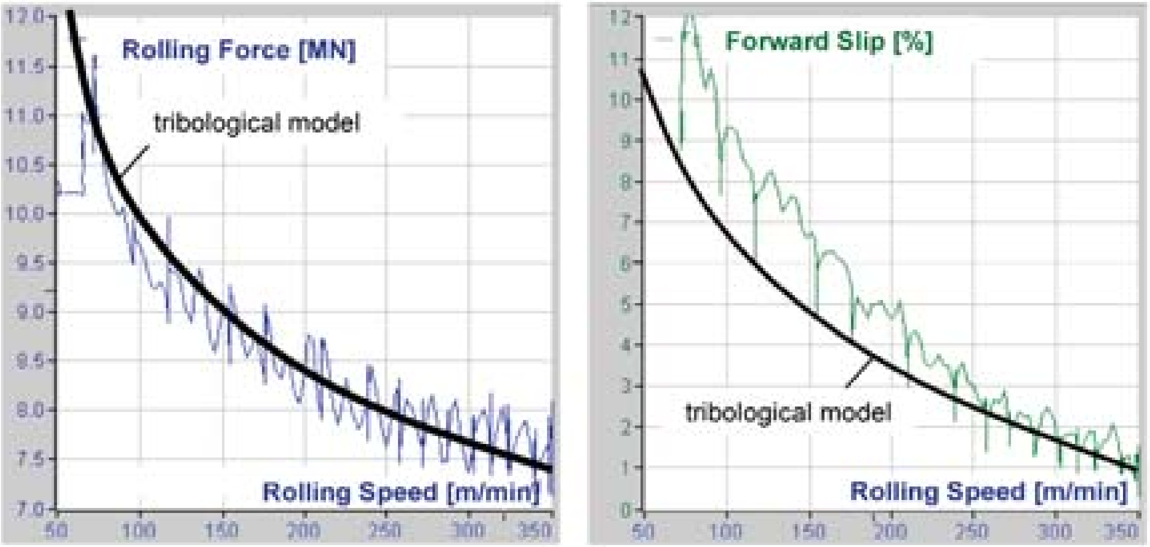


Figure 16: Comparison of the measured and calculated process variables (rolling force, forward slip), in cold rolling.

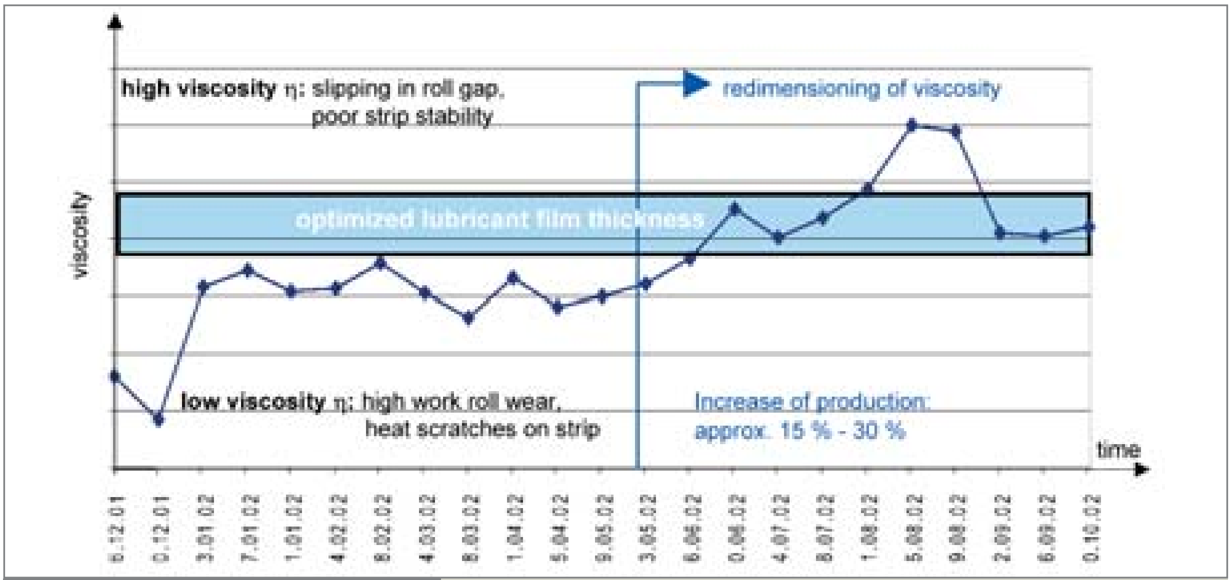


Figure 17: Optimisation of roll gap lubrication with aid of tribological model.

Another constituent part of the tribological model determines the progression of the fractional area of contact in the roll gap as a result of the increase in pressure and of the deformation of the surface roughness of the material to be rolled [8]. Both cause an increase of the coefficient of friction between the entry and the delivery side. This repercussion was confirmed by measured process data (cf. **Figure 16**). To achieve these results, just an adaptation constant (the microscopic coefficient of friction) was used. The progression of the fractional area of contact is directly connected with the transfer of the work roll roughness onto the strip. Another module of the model is thus an approximation of the surface roughness of the rolled strip (cf. Figure 13).

On the CVC4-HS cold mill stand of TKES Gelsenkirchen (manufacturer of grain-oriented silicon steel) optimisations of the rolling process were performed with the help of the cold rolling process model including the tribological model (T-roll).

The lubricant conditions, the temperature progression and the pass schedule were optimised in cooperation with TKES on the basis of the understanding of the physical process. An important parameter is for example the base-oil viscosity of the emulsion, **Figure 17.** Too high viscosity (too low friction) leads to slippage and instability in the roll gap while too low viscosity (too high friction) causes heat scratches on the strip surface together with great roll wear.

Furthermore, the pass schedules were improved with a view to a higher rolling speed, optimised reductions and the possibility of reducing the number of passes. The results of the optimisation activities are shown in Figs. 18 and 19. The productivity of the rolling mill was increased significantly for all silicon steel grades during the period indicated (ca. 15 – 30 % on an average). This success was mainly achieved by a more stable rolling process (few strip breaks) at a higher speed level (Fig. 18).

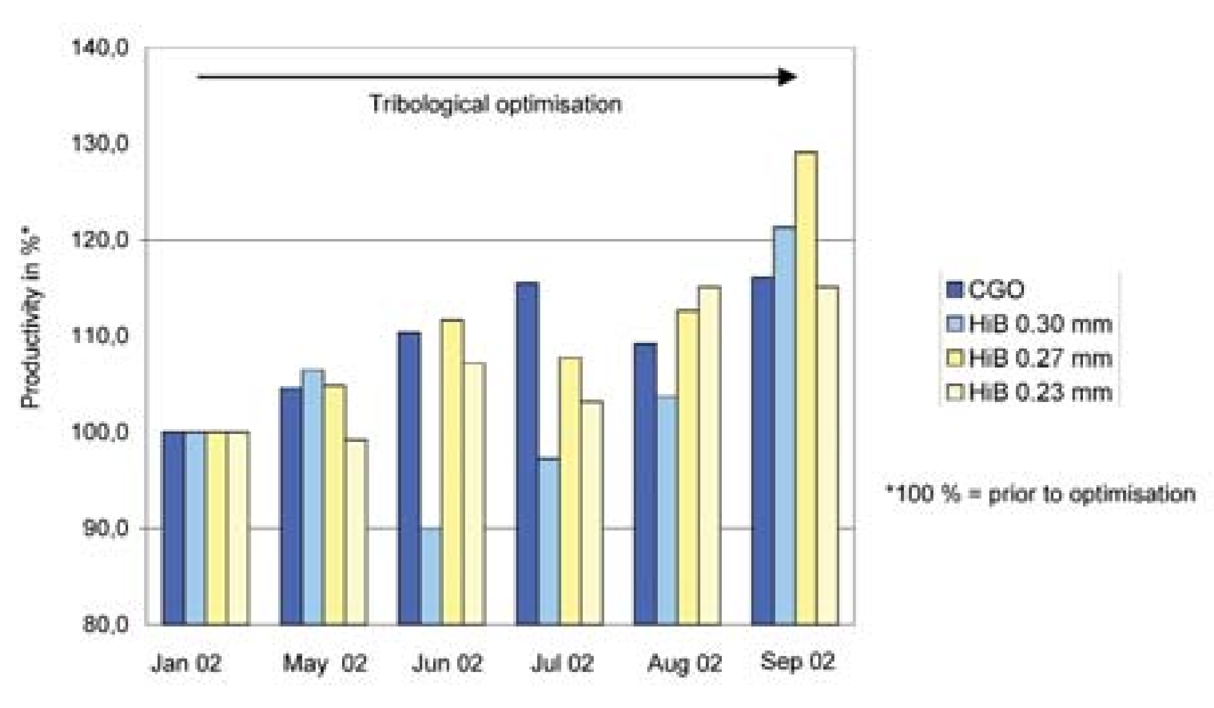


Figure 18: Cold rolling of high grain-oriented silicon steel.
Production increase during tribological optimisation.

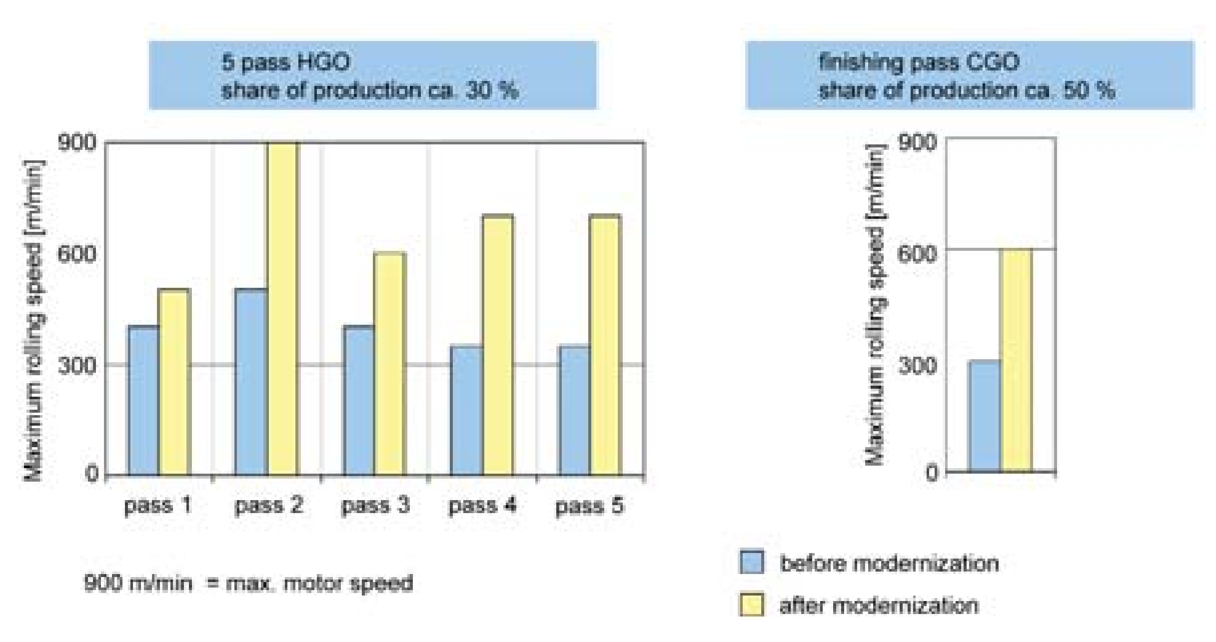


Figure 19: Cold rolling of high grain-oriented silicon steel.
Increase of the maximum speed during the tribological optimisation.

Outlook

New technologies were developed, implemented in process models and control systems and successfully put into operation for the hot and cold rolling of high-strength steel qualities. The results achieved document the effectiveness of these developments.

The users of hot and cold rolling mills now possess technological concepts that in conjunction with targeted mechanical modernisations offer the opportunity of manufacturing the new, complex steel materials with a high productivity and product quality.

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For your notes

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