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Developments in hot-rolled high-strength structural steels

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Recently developed high-strength structural steels from Ruukki are described together with some of their technological properties. New hot strip mill products include steels with yield strengths up to 1100 MPa, while from the plate mill, thermomechanically processed steels with yield strengths 500 and 690 MPa are now available. The new direct-quenched plate-mill products planned for 2007 are also briefly described.

Rautaruukki supplies metal-based components, systems and integrated systems to the construction and mechanical engineering industries. The Corporation has used the marketing name Ruukki since 2004. Ruukki has three divisions with overall customer responsibility: Ruukki Construction, Ruukki Engineering and Ruukki Metals. Ruukki Construction supplies metal-based solutions for building and infrastructure construction. Ruukki Engineering supplies metal-based solutions for the lifting, handling and transportation equipment industries, for paper and wood processing, and for the marine and offshore industries. Ruukki Metals supplies a wide selection of steel, stainless steel and aluminium as standard and special products, parts and components. A fourth division, Ruukki Production, manufactures hot-rolled and cold-rolled flat steel products together with steel tubes and profiles for the divisions with customer responsibility. The aim of this article is to describe new and coming developments in the area of hot-rolled structural steel made by the steelworks of Ruukki Production at Raahe.

During recent years, hot-rolled steel development in Ruukki has been focussed on increasing the strength and dimension ranges of the product portfolio, especially in the field of structural steel. This has been driven by the demand for increasingly higher strength levels from the market as experience with the application and use of such steels grows. Higher strengths offer the designer the possibility of making lighter, higher performance structures with good overall cost effectiveness together with lower environmental impacts. The use of high-strength steel can mean lower fabrication costs, increased payloads, more durable products, more effective space utilization and increased safety. On the other hand, the production and use of high-strength steel sets higher demands on the steelmaker, the designer and the fabricator.

In Ruukki, hot-rolled steels are produced in two ways: via the hot strip mill and via the plate mill. The production route governs the dimension ranges of the final plates such that strip mill products offer lower minimum thickness and excellent thickness tolerances while the plate mill products extend to larger maximum widths and thicknesses. During recent years, product development has led to new high-strength structural steels from both the plate and strip mill. From the strip mill, these include a series of martensitic proprietary grades called Optim 900 QC, Optim 960 QC and Optim 1100 QC. In the case of the plate mill, new low-carbon thermomechanically processed structural grades in the yield strength classes 500 and 690 MPa have been developed. Currently, much effort is being directed at the development of high-strength direct-quenched plate-mill products.

- **Ultra-high-strength products from the hot strip mill**
  Ultra-high-strength steels are conventionally manufactured from hot-rolled plate by reheating, quenching and tempering. There is, however, a demand for ultra-high-strength steel with improved surface quality, thicknesses not normally available as plate and tight thickness tolerances. In order to meet these demands, Ruukki Production explored alternative production routes, which resulted in new hot strip mill products with yield strengths 900 and 960 MPa. The products have the proprietary names Optim 900 QC and Optim 960 QC.

  In the development of these steels, the aim was to achieve the required yield strength levels in combination with good impact toughness, weldability, formability and suitability for hot dip galvanizing. In addition, consideration was given to the increasing demand for suitability to laser cutting and welding. Therefore, the steel composition was based on as low a low carbon content as possible in order to ensure good weldability, as defined by preheating requirements and heat affected zone toughness, good flangeability and suitability to laser processing. Silicon was limited to below 0.25% in order to ensure good hot dip galvanizing properties and to prevent any problems with red scale, which would impair surface quality. Manganese was maintained below 1.2%, which together with the low carbon content keeps centre-line segregation to a minimum and improves the flangeability of sheared edges. Similar advantages are gained by keeping phosphorus and sulphur contents low and by modifying the sulphide inclusions using calcium treatment. These basic composition limitations are shown in Table 1. Keeping within these limitations, suitable levels for other alloying elements such as chromium and molybdenum were determined with the aid of full scale rolling trials. By choosing the hot strip mill as the production route, it was possible to achieve very good surface quality and thickness tolerances. This work resulted in combinations of chemical composition and processing parameters that result in fine-grained martensitic – bainitic microstructures like that shown in Figure 1. Specified minimum mechanical properties are given in Table 2.

Basic chemical composition limits (wt.%) and carbon equivalent values *Table 1*

Optim grade	C max	Si max	Mn max	P max	S max	Ti max	CEV typical	CEV max
900 QC	0.10	0.25	1.15	0.020	0.010	0.07	0.46	0.51
960 QC	0.11	0.25	1.20	0.020	0.010	0.07	0.47	0.52

CEV = C+Mn/6+(Cr+Mo+V)/5+(Cu+Ni)/15

Specified minimum tensile and Charpy V impact properties *Table 2*

Optim grade	$R_{p0.2}$ min, MPa	R_m min, MPa	A_5 min, %	Impact toughness at -40°C longitudinal, min., J
900 QC	900	950	8	50 [1)]
960 QC	960	1000	7	50 [1)]

[1)] Values given for 10 x 10 mm specimens. For 5 mm thick material KV min = 33 J.
For thicknesses between 5 & 10 mm, required min value linearly interpolated between 50 & 33 J.

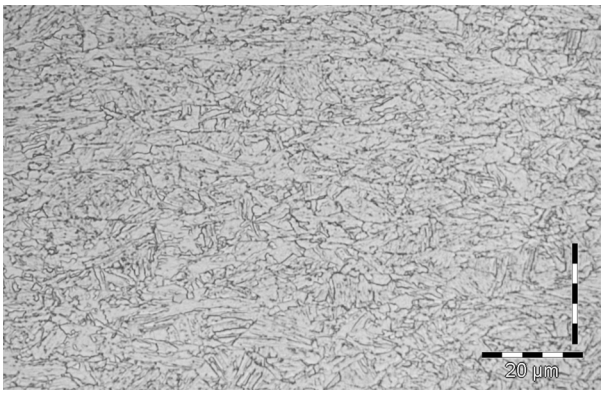

Fig. 1. Typical microstructure structure of the ultra high strength steel. Light optical micrograph, nital etching, length of micron bar 20 µm.

The hot strip mill produces coils of steel that are subsequently uncoiled, leveled and cut to length. In this way, plates with thicknesses of 2.5 - 6.4 mm, widths up to 1560 mm, and lengths of 2 to 12 m are currently produced.

The good technological properties of Optim 900 and 960 QC have been demonstrated in forming, welding, cutting and fatigue testing programmes.

Flanging in a brake press to relatively small inside bend radii is possible, but due to the very high strength of the material the equipment must be capable of handling sufficiently high loads and the tooling must be of high quality. The recommended minimum internal bend radius is 3 times the material thickness for Optim 900 QC and 3.5 times the thickness for Optim 960 QC.

Roll forming of Optim 900 QC has been done on the production line at Ruukki's Toijala works. Trials were made using 4 mm thick material slit into 382 mm wide strips. The roll forming of the 13.5 m long U profiles shown in Fig. 2a succeeded without major difficulties, although the different spring-back of the ultra-high-strength steel compared to that of the lower strength grades normally run on the line had to be taken into account. The inner radius of the 90 degree corner is 6 mm. The straightness and shape of the profiles fulfilled requirements and the roll forming process has subsequently been used to make profiles for the beams in the mobile aerial platforms shown in Figure 2.

Fabrication trials have also demonstrated that these ultra-high-strength steels can be successfully cold formed and high-frequency welded into pipes and rectangular hollow sections.

Ultra-high-strength martensitic steels are more sensitive to hydrogen than ferritic-pearlitic steels. Consequently, tests have been performed to investigate the influence of pickling on the properties of Optim 900 QC. Slow speed tensile and bending tests 1 hour and 1 week after pickling showed, however, that there was no detrimental effect of pickling on mechanical properties.

Hot-dip galvanizing tests using Optim 900 QC have shown that the best adhesion of the zinc layer is obtained with short dipping times, giving a zinc layer thickness of less than 100 µm. The heat of the galvanizing process reduces the tensile strength only very little, whereas yield strength is increased somewhat, giving

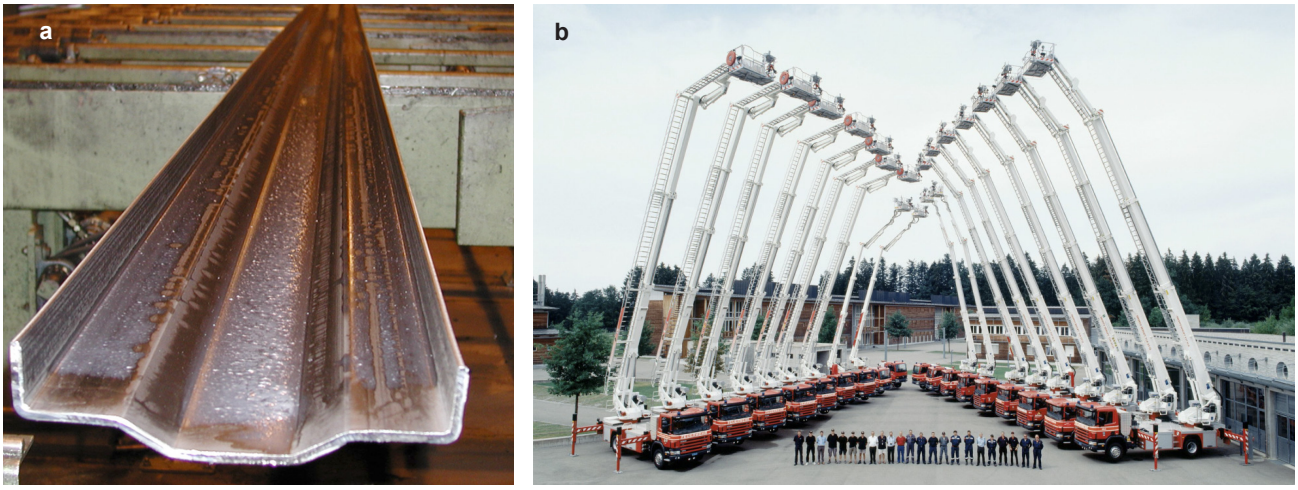

Fig. 2. U profile roll formed from Optim 900 QC (a). Beam used aerial platform (b).

yield to tensile ratios close to unity after galvanizing. As regards the thickness and quality of the zinc layer, Optim 900 QC behaves as expected for steel with a Si+P content of about 0.2%. Hot-dip galvanizing properties fulfil class 3 of EN 10025.

Laser cutting tests have been made using 4 mm thick Optim 900 QC. The cut edge is slightly hardened, but below this is a narrow softened zone, about 0.2 mm wide, where the lowest hardness values were about 60 HV0.2 lower than in the base material. The fatigue properties of laser cut materials were determined in tests at 20 Hz with a stress ratio R = 0.1. The results indicate that the fatigue limit for laser-cut Optim 900 QC approaches 500 MPa, i.e. more than half of the yield strength.

The weldability of Optim 900 QC and 960 QC plates with thicknesses 3 and 6 mm has been investigated for MAG, Laser and Laser hybrid welding. Using conventional MAG welding, it is difficult to achieve overmatching butt welds. This is due to the fact that at such small thicknesses heat flow is two-dimensional and cooling times, which are inversely proportional to the plate thickness, tend to be rather long. Also, heat affected zones are relatively wide when compared to the plate thickness. For these reasons conventional narrow cross-weld tensile specimens often fail in the HAZ (or the weld metal) even with heat inputs as small as 0.5 kJ/ mm. The tensile strength properties of the base plate can, however, be achieved by using hydrid MAG-Laser welding, while autogenous Laser welds show both yield and tensile strengths that exceed those of the base plate. Recently, it has been shown that the extent of the softened zones can be reduced by using pulsed MAG welding to reduce cooling times. Of course, the presence of soft zones can be tolerated by taking the softening into account at the design stage. Often welds in high-strength steels are made with undermatching consumables too, for example by locating the welds in regions of low stress or by adjusting the throat thickness in the case of fillet welds.

Charpy V impact toughness requirements are met at -20°C in the weld metal and HAZ of MAG welds when the cooling time from 800 to 500 ($t_{8/5}$) is less than 15 s, corresponding to an arc energy of 0.8 kJ/mm in a 6 mm thick plate. Impact test requirements at lower temperatures can be met by using lower arc energy. In practice, the impact toughness requirement and allowable arc energy will depend on the location of the weld, the stresses in the region of the weld and the minimum design temperature.

Butt welds in Optim 960 QC have shown good fatigue behaviour. FAT 95 values of 131 and 170 MPa have been obtained for Laser-hybrid and MAG welds respectively. These values are well above the normal design value for this type of weld, i.e. $\Delta\sigma$ = 80 MPa.

The latest development from the hot strip mill is a steel called Optim 1100 QC. As its name implies, this is a similar steel to Optim 900 and 960 QC, but with a specified minimum yield strength of 1100 MPa. This product is in the trial delivery stage so that exact specification details are not yet available.

- **New low-carbon low-temperature structural steels from the plate mill**
  In the case of hot-rolled, normalized or normalizing-rolled plate-mill products, high strengths are associated with high levels of alloying elements raising the carbon

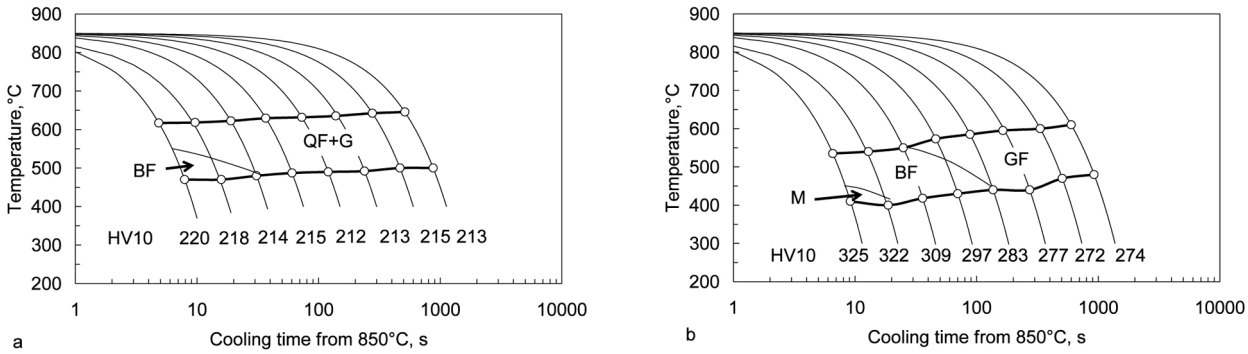

Fig. 3. CCT diagrams for two very low carbon steel compositions after simulated thermomechanical treatment at 850oC. QF = quasipolygonal ferrite, GF = granular bainitic ferrite, BF = bainitic ferrite, M = martensite. (a) lean chemical composition Pcm = 0.17, CEV(IIW) = 0.48, (b) richer composition P_{cm} = 0.23, CEV(IIW) = 0.63.

Chemical composition parameters for PC F500 W *Table 3*

C max	Si max	Mn max	P max	S max	Al max	Cu max	Ni max
0.04	0.55	2.15	0.020	0.007	0.055	0.30	1.0
Cr max	Mo max	V max	Nb max	Ti max	N max	B max	P_{cm} max
0.25	0.25	0.08	0.05	0.025	0.009	0.0005	0.22

P_{cm} = C + (Mn+Cr+Cu)/20 + Si/30 + Ni/60 + Mo/15 + V/10 + 5xB

Specified minimum tensile and Charpy V impact properties for PC F500 W *Table 4*

Thickness mm	$R_{p0.2}$ min, MPa	R_m MPa	A min, %	Charpy V, -70°C, trans. min mean/min indiv., J
18 – 50	500	610 - 770	16	60 / 42

equivalent and making welding more difficult due to the need for preheating. Strength can be raised with no increase in carbon equivalent by reducing the grain size. This is achieved by rolling the steel below its recrystallization temperature, i.e. by thermomechanical rolling, especially in combination with accelerated cooling. Microstructurally, such steels are usually mixtures of fine polygonal ferrite and bainite. This approach has been the basis of earlier developments in Ruukki and resulted in the addition of the EN 10025-4 grades S420M - S460ML to the production programme.

As a result of the demand for still higher strengths, Ruukki also produces a similar grade Optim 500 ML having a yield strength of 500 MPa, which is not covered by the standard EN 10025-4. A similar shipbuilding grade NVE 500 has also been developed for use in ice-breakers. These thermomechanically processed steels with a yield strength of 500 MPa have very good weldability: carbon contents are in the range of about 0.07 – 0.14% and carbon equivalents no higher than those of normalized fine-grain steel with a yield strength of 355 MPa, i.e. typically about 0.40 on the IIW scale. Optim 500 ML is produced in thicknesses up to 40 mm with impact toughness values better than 27J at -50°C. However, using this approach, it is has been found to be uneconomical, at this strength level, to extend the product spectrum to greater thicknesses than 40 mm or to lower the impact test temperature to below -40°C. There is, however, a demand for economical thermomechanically processed 500 MPa steel to thicknesses greater than 40 mm with impact toughness testing at temperatures down to as low as -70°C. There is also a demand for still higher strength thermomechanically processed steel. These demands led to the instigation of development programmes, the result of which are new thermomechanically processed structural steels with minimum specified yield strengths of 500 and 690 MPa.

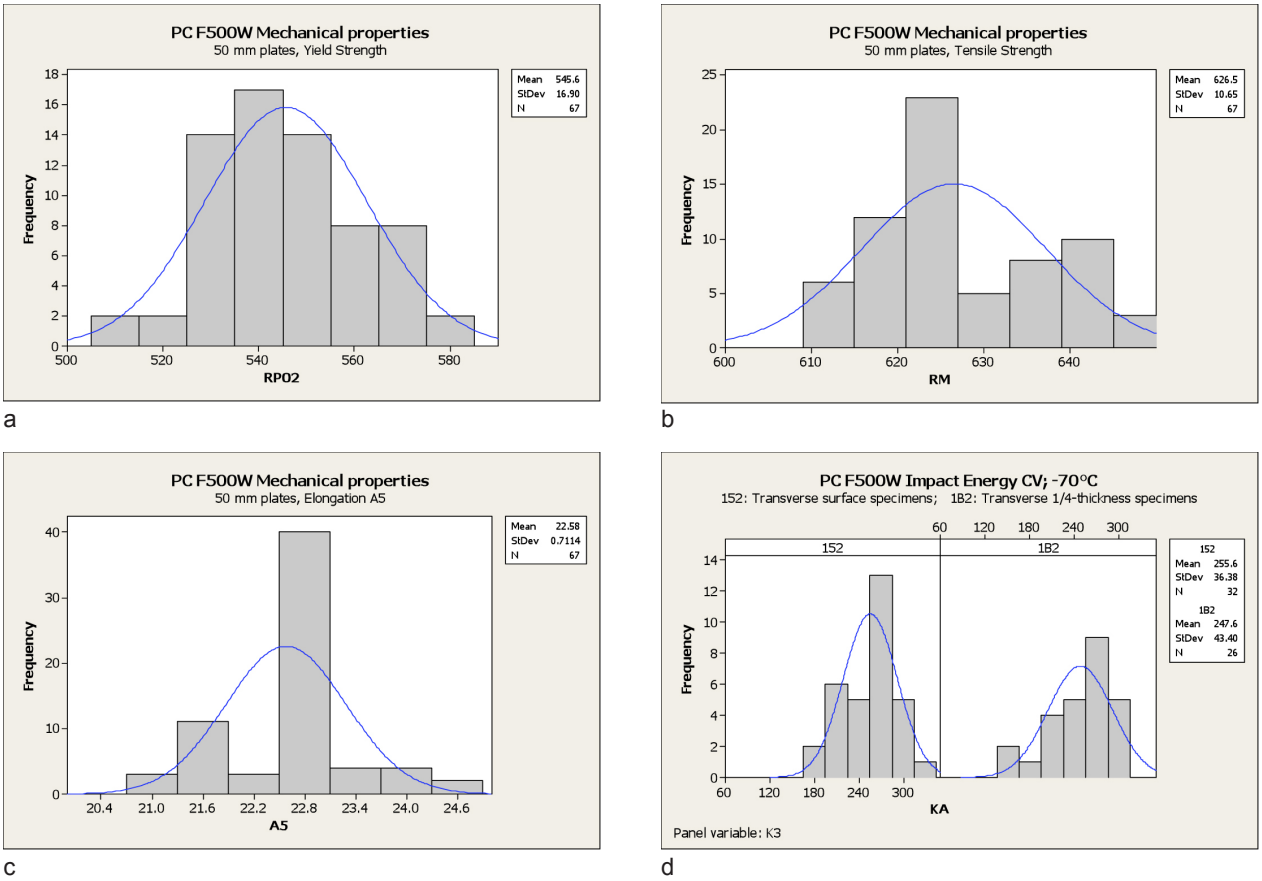

Fig. 4. Mechanical properties of PC F500 W. a) Yield strength, σ = 16.9 MPa, b) tensile strength, σ = 10.7 MPa, c) elongation to fracture, σ = 0.7 %, d) Charpy V impact toughness at -70oC with transverse specimens at the surface and quarter-thickness positions, σ = 36 and 43 J respectively.

Compared to earlier thermomechanically processed steels, the new steels are based on lower levels of carbon (< 0.05%) together with niobium and molybdenum. In addition, elements such as chromium, nickel and boron have been found to be useful. After thermomechanical processing, such chemistries lead to the formation of one or more of the following microstructural constituents: quasipolygonal ferrite, granular bainite, bainite and martensite. As the level of alloying is increased, the phase transformation temperatures are reduced and this leads to higher strengths as shown in Fig. 3. In the case of lean chemistries, which transform to quasipolygonal ferrite and granular bainite, the strength is almost insensitive to the cooling rate as shown by the hardness values in Fig. 3a. It is believed that this is due to an increasing strength contribution from niobium carbide precipitation as the cooling rate decreases, and that this compensates for the loss of strength caused by the higher phase transformation temperatures and diminishing dislocation strengthening.

- **PC F500 W**

  Using the very-low-carbon approach, it has been possible to develop new thermomechanically processed steels for applications requiring high strength and good low-temperature toughness. The first deliveries of such a steel with a yield strength of 500 MPa have been made to the Russian jack-up offshore platform project Arktichskaya 100. The grade in question is the shipbuilding grade PC F500 W. Tables 3 and 4 summarise its chemical composition and mechanical properties. It is also envisaged that the same approach will result in steel that meets the requirements of the offshore steel S500G2+M in accordance with Norsok M120.

  Fig. 4 shows mechanical property statistics for PC F500 W. The small scatter in properties is due to the robustness of the chosen production route. As noted above, the very low carbon content makes the strength properties relatively insensitive to changes in cooling rate. The microstructure is mainly quasipolygonal ferrite as shown by Figure 5.

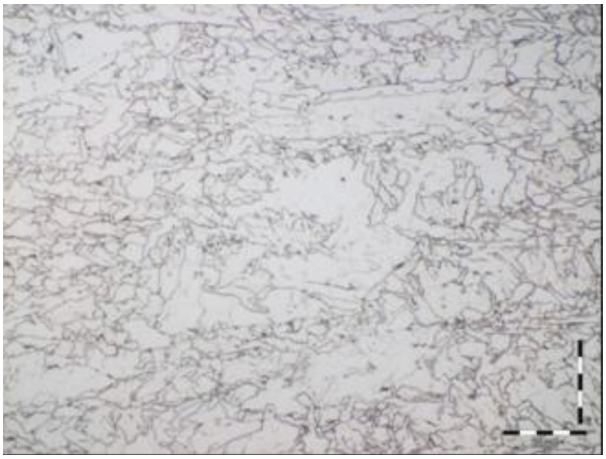

Fig. 5. Microstructure of PC F500 W. The micron bars are 20 µm long. Nital etching, light microscope.

Fig. 6. S 700 ML has been applied to log handling equipment manufactured by Loglift.

The weldability of PC F500 W is good. As a result of the very low carbon content, the hardness of the heat affected zone always remains low. It is important to recognize that the weldability of these low-carbon grades is best described by the parameter P_{cm}, which remains below 0.22, despite the high strength level. The widely used IIW weldability parameter CEV cannot be used to estimate the preheat requirements when the carbon content is as low as 0.04% or less. Weldability testing of PC F500 W has shown that 50 mm thick plates can be welded with heat inputs in the range 0.65 – 3.5 kJ/mm: impact toughness requirements were fulfilled at -60°C, cross-weld tensile tests failed in the base plate, and the maximum hardness measured in the HAZ was 258 HV10. In CTS tests without preheat, welding at a heat input of 1 kJ/mm with an overmatching weld metal gave a maximum hardness in the HAZ of 285 HV10 and no hydrogen cracking.

- **S 700 ML**

The increased demand for structural steel with a minimum specified yield strength of 690 MPa has increased interest in thermomechanically rolled plate as an alternative to conventional quenched and tempered steels such as S690Q/QL/QL1 (EN 10025-6). As can be seen from Figure 3b, after thermomechanical processing very low carbon contents in combination with suitable levels of alloying elements can lead to granular bainitic or bainitic microstructures with hardness levels equivalent to those of S690, i.e. about 270 HV10. This new approach to obtaining S690 properties has been successfully applied in production and has resulted in the launching the new plate mill product S 700 ML, which has been successfully applied in lifting and forestry equipment as shown for example in Figure 6.

Information regarding the chemical and mechanical properties of S 700 ML are given in Tables 5 and 6. As regards mechanical properties, S 700 ML is equivalent to S 690 QL in EN 10025-6 (or the old standard EN 10137-2). Due to the very low level of carbon, the composition of S 700 ML does not remain within the composition limits of EN 10025-6, but this has no deleterious effects on properties. As a result of the very low level of carbon in the steel, the conventional IIW carbon equivalent is rather high when compared to quenched and tempered S690Q/QL/QL1 grades. In the case of 20 mm thick S 700 ML CEV(IIW) is typically 0.60 whereas a value of 0.50 is typical for S690Q/QL grades. CEV(IIW) is an appropriate parameter for quenched and tempered steels with carbon contents greater than 0.13%. However, it is quite inappropriate when C < 0.05% where Pcm is better. Pcm for the new S690ML is below 0.26. In practice, for S 700 ML preheating practice will be governed by the requirements of the welding consumable and not by the steel plate. For plate thicknesses up to 20 mm, preheating will not normally be required. Welding heat input depends on the strength and toughness requirements of the joint. To some extent, the thermal cycle experienced by the weld can be characterized by the cooling time between 800 and 500ºC ($t_{8/5}$). Preliminary welding tests have shown that cooling times ($t_{8/5}$) in the range 5 – 20 s are appropriate for S 700 ML. These values are similar to those recommended for quenched and tempered steels in the same strength class. Early experiences from flame straightening trials have shown that the new low-carbon thermomechanically processed S 700 ML is less sensitive to overheating than equivalent conventional quenched and tempered grades. On the other hand, S 700 ML is not suitable for applications requiring stress relief heat treatment after welding (PWHT).

Chemical composition parameters for S 700 ML *Table 5*

C max	Mn min	Cu max	Ni max	Cr max	Mo max	V max	B max	P_{cm} max
0.05	1.5	0.5	1.0	1.5	0.5	0.05	.005	0.26

Pcm = C + (Mn+Cr+Cu)/20 + Si/30 + Ni/60 + Mo/15 + V/10 + 5xB

Specified minimum tensile and Charpy V impact properties for S 700 ML *Table 6*

Thickness mm	$R_{p0.2}$ min, MPa	R_m MPa	A min, %	KV -40°C, transverse min mean, J
15 – 40	690	770 – 940	14	30

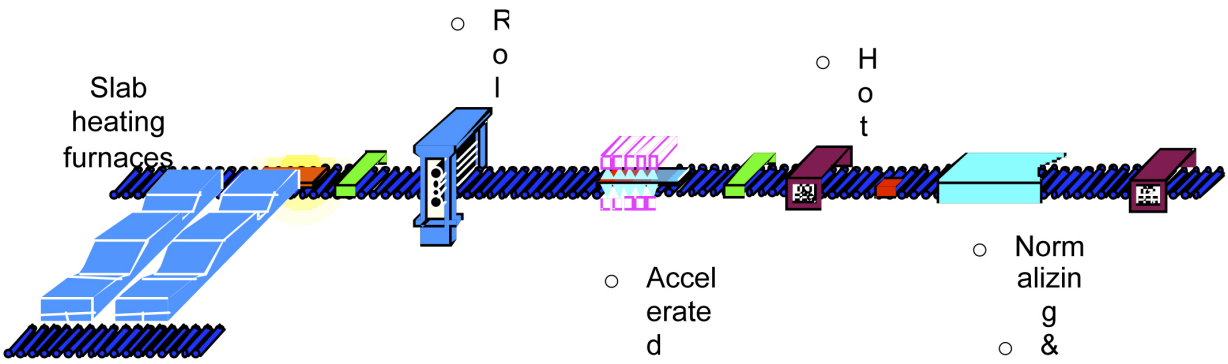

Fig. 7. Present layout of the first part of the plate mill at Raahe steel works

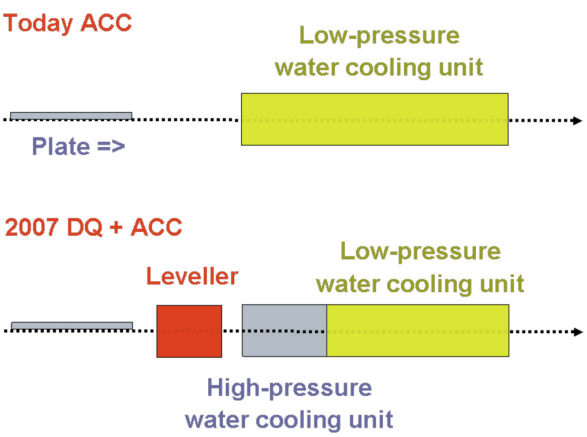

Fig. 8. Schematic diagram showing how the present accelerated cooling unit (ACC) will be changed into a combined direct quenching and accelerated cooling unit (DQ + ACC).

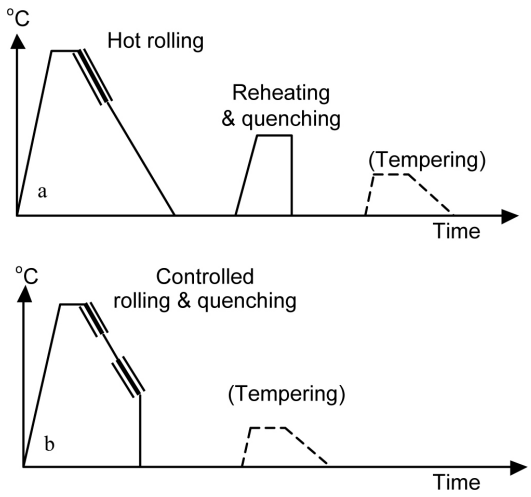

Fig. 9. Schematic time - temperature diagrams showing the difference between conventional off-line quenching (a) and direct quenching (b).

- **Quenched products from the plate mill in 2007**
  In order to be able to produce quenched plate mill products, Ruukki is in the process of adding direct quenching equipment to the existing accelerated cooling unit. Figure 7 shows the plate mill as it is today with an accelerated cooling unit after the rolling stand. The modifications that are being undertaken are shown in Figure 8. The existing low-pressure water cooling unit will be shortened to allow the addition of a high-pressure quenching unit. Also, a hot leveller will be added in front of the quenching unit to ensure that the plates are flat prior to quenching. This will help ensure uniform quenching and the achievement of good flatness in the final plate. Compared to the present accelerated cooling process, the new set-up, which will be in operation in the second half of 2007, will allow higher cooling rates and cooling to lower temperatures. It will then be possible to produce steel plates based on martensitic microstructures, i.e. hard abrasion resistant steels and quenched and tempered structural steels.

  Metallurgically, direct quenching is a more versatile process than conventional reheat quenching, offering more possibilities for microstructural control. Direct quenching leads to a higher hardness for a given chemistry, which can be converted into products with lower carbon equivalents and better weldability. By using thermo-mechanical rolling, finer microstructures with improved toughness are also possible. In addition, surface quality can be improved by using scale washing during rolling.

  Combining rolling and quenching into a single process also has logistical advantages over conventional reheating and quenching helping to make delivery times shorter and more precise.

  Development projects are currently under way in preparation for the introduction of the direct quenching equipment. The new products envisaged are wear resistant quenched plates and quenched and tempered structural plates. Wear resistant plates will have Brinell hardness levels of 400, 450 and 500, whereas the structural steels will be according to EN 10025-6, starting with S690Q/ QL.

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