

State of art in the production and use of high-strength heavy plates for hydropower applications¹

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1. Introduction

The global energy consumption is strongly growing. Even though improved technology allows to exploit the reservoirs more completely and to extend production into deeper water and harsher environment, the prospects of fossil fuels decline rapidly. Increasing fuel prices make alternative energy resources like hydropower more and more attractive. For a steel plate producer, the penstock pipe and the pipework in the powerhouse is the most interesting part of a hydropower plant, especially if increasing water pressure and pipe dimensions ask for thick plates and give advantage for the use of high strength steels.

In this context the hydro power plant Bieudron Dixence in Switzerland is a rather unique due to the extreme head height of almost 1900 m. Because of the important pressure in the penstock a steel of a minimum yield strength of 890 MPa had initially been selected for the lower part of the penstock in order to reduce the weight of the individual shells, to increase the length of preassembled pipe segments that could be handled in the tunnel and to reduce the number of circumferential welds on site.

The failure that happened in the penstock after some months of service, must not generally exclude S890Q steel from future use in penstock pipes. Until the causes of the accident are fully understood it seems wise for the repair work to apply steel of a lower strength level. An argument for a lower strength is that it is easier to produce weld metal of adequate toughness and strength properties. These materials need less care in welding and allow welding with higher deposition rates. Pipes of lower strength are also likely to tolerate larger defects, to have higher crack arrest properties and react less susceptible to a hydrogen pick up in operation [1].

This paper shall explain the principles of the production of different high strength grades. The modern rolling and heat treatment processes for the production of high strength heavy plates will be described and examples given for properties achieved by

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quenching and tempering and thermomechanical rolling. Aspects of the weldability will finally be considered.

2. Production of high strength heavy plates

One prerequisite for plates that combine high strength with high toughness is to produce a very clean steel, for minimising oxide and sulphide inclusions and harmful trace elements. Figure 1 shows which improvements the steel shop of Dillinger Hütte has reached over the years [2] by applying: secondary metallurgy, ladle refinement and vacuum degassing. Reduced contents of impurities in the steel, such as phosphorus, sulfur, nitrogen and oxygen are beneficial for the parent material, the HAZ and give advantages for the processing [3].

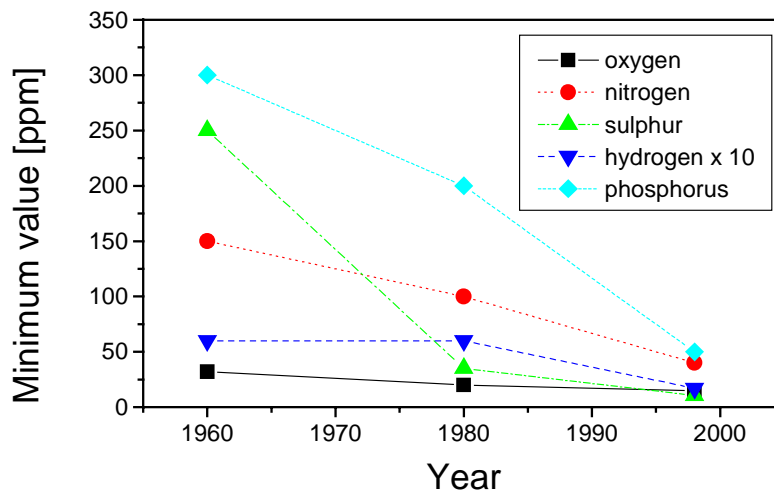


Fig. 1: Attainable contents of impurities by improvement of steel making technology at Dillinger Hütte.

Delivery conditions

Weldable structural steels are delivered in the conditions: normalised, quenched and tempered and thermomechanical controlled rolled, schematically shown in figure 2. Figure 3 allows to compare typical microstructures for the above mentioned supply conditions.

For steel grades of moderate strength and toughness requirements a classical hot rolling and **normalising** of the steel is sufficient to obtain the necessary mechanical values. By this process route weldable structural steels up to S460N are produced. Hot rolling is generally carried out at high temperatures above 950°C (process A in figure 2). By reheating the hot rolled plates to some 900°C followed by free cooling in air a refined microstructure of ferrite and pearlite (process B in figure 2) is obtained.



By **quenching and tempering** structural steels can reach a yield stress of up to 1,100 MPa. This heat treatment (process C in figure 2) applied subsequent to hot rolling, consists of an austenitisation, followed by quenching and finally tempering.

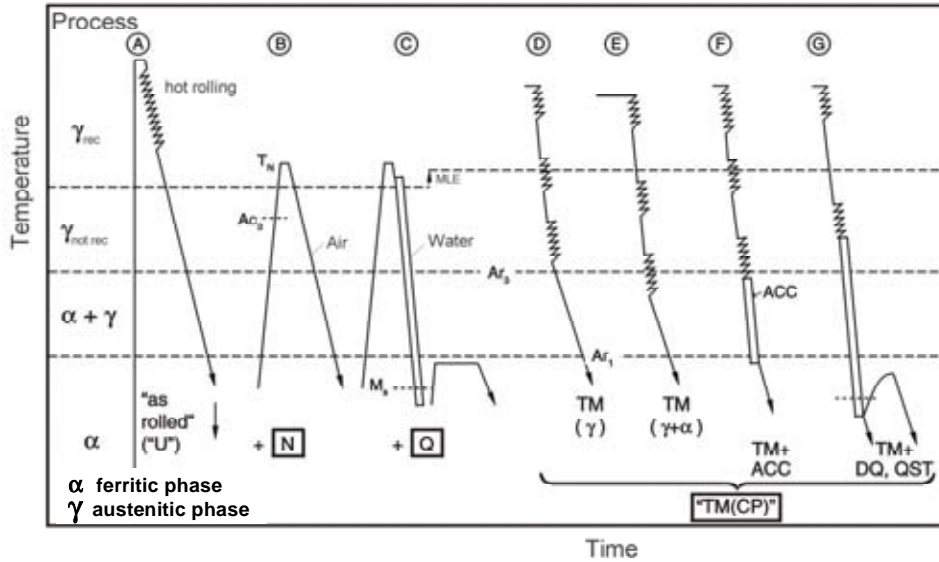


Fig. 2: Schematic temperature-time-procedures used in plate production: normalized (process A+B), quenched and tempered (precess A+C) and different TMCP processes (D - G) [4]

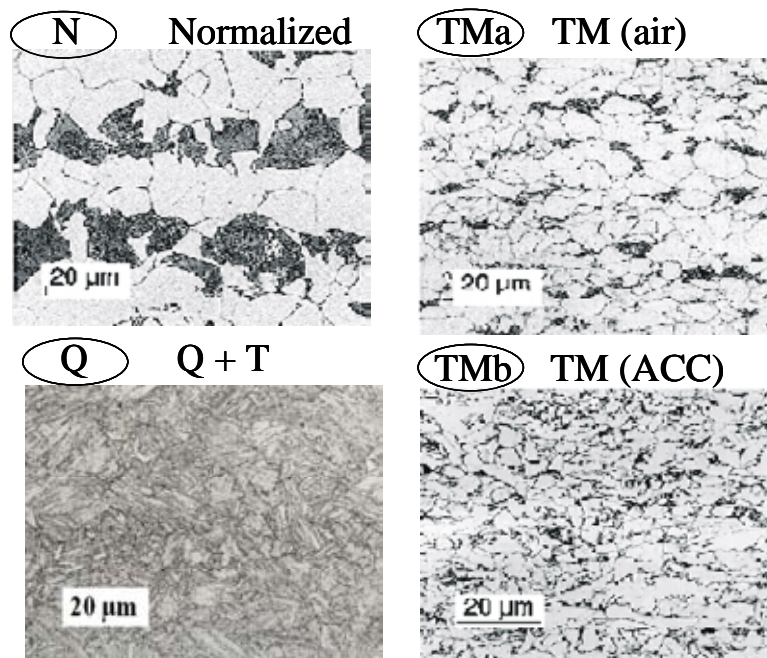


Fig. 3: Microstructure of conventional normalised steel (process B of Figure 2) compared to TMCP (process D), TMCP+ACC (process F) and Q+T steel (process C)

The aim of **thermomechanical rolling** (TM or TMCP) is to create an extremely fine grained microstructure by a skilled combination of rolling steps at particular temperatures and a close temperature control. The gain in strength obtained by the grain refinement allows to reduce effectively the carbon and alloy content of the TM-steel compared to normalised steel of the same grade. The improved weldability that results from the leaner steel composition, is a major advantage of the TM-plates. Depending on the chemical composition, the required strength and toughness properties and the plate thickness the "rolling schedule" is individually designed. Some typical TM-processes are shown in figure 2. Especially for thick plates an **accelerated cooling** after the final rolling pass is beneficial for the achievement of the most suitable microstructure as it forces the transformation of the elongated austenite grains before recrystallisation can happen. For very thick plates and higher yield strength grades a tempering process can be used after the accelerated cooling.

TM-rolled plates with minimum yield strength values of 500 MPa were supplied up to 100 mm for hydropower, offshore platforms and special ships [5]. Even higher yield stress classes up to 690 MPa are feasible by the TM-process, however, in a more limited thickness.

3. Quenched and tempered high strength steel

Steels of 690 MPa yield became commercial about 3 decades ago. They were – like today- essentially produced by water quenching and tempering (QT). Nowadays QT-plates with a yield strength over 1100 MPa have become commercial.

The aim of quenching and tempering is to produce a microstructure consisting mainly of tempered martensite. Some amounts of lower bainite are also acceptable. Quenching of high strength steels is performed after austenising at temperatures of 900-960°C. In order to suppress the formation of softer microstructure, essentially ferrite, during cooling an accelerated cooling is necessary. The fastest cooling is obtained by exposing the plate surfaces to a rapid water stream. By such an operation the very surface is cooled to temperature below 300°C within a few seconds. In the core of the plate cooling is considerably slower and the cooling rate decreases with increasing plate thickness. Table 1 compares the average rates of free cooling in still air with the ones attained by water cooling. At the core of thick plates the heat flow to the surface is the controlling parameter for the cooling rate. Closer to the surface and for thinner plates also parameters controlling the heat transfer, e.g. water temperature or flow rate, are of importance.

Table 1: Comparison of cooling rates for subsurface and mid-thickness of a plate

Plate thickness	Air cooling	Water-cooling subsurface	Water-cooling mid thickness
20 mm	0.5 K/s	80 K/s	40 K/s
100 mm	0.1 K/s	80 K/s	2.5 K/s

If we consider the mechanical properties in the as quenched condition, the strength is considerably higher than required but the material is too brittle for most structural applications. A suitable tempering of the martensitic microstructure is necessary in order to get a satisfactory combination of tensile and toughness properties. By tempering the martensite, the supersaturation of carbon in the matrix is reduced by the precipitation of carbides leading to a relaxation in the atomistic scale. At the same heat treatment the high dislocation density associated with martensite formation is reduced. Both effects improve the toughness of the material. A 60 mm thick S890QL (EN 10137) is chosen for example that shows the influence of tempering on the properties. Figure 4 shows how the tensile properties are lowered with increasing temper parameter, figure 5 the improvement of impact toughness, respectively.

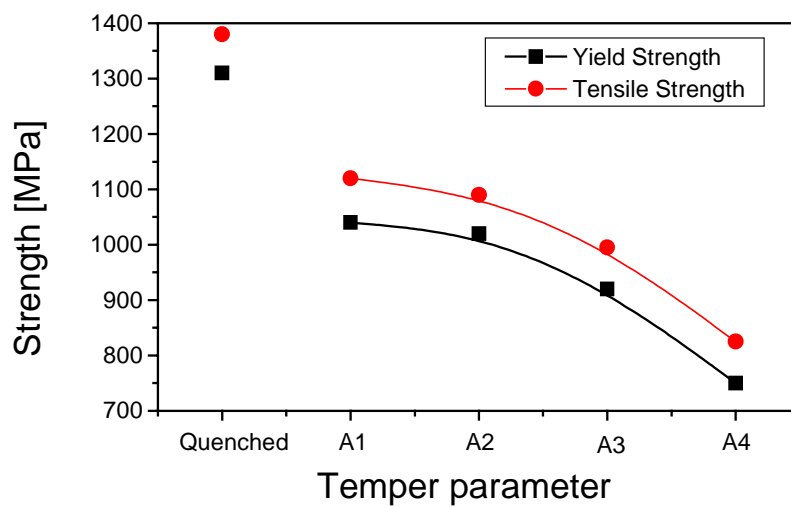


Fig. 4: Influence of increasing tempering temperatures on the tensile properties of Dillimax 890 in 60 mm thickness [6]

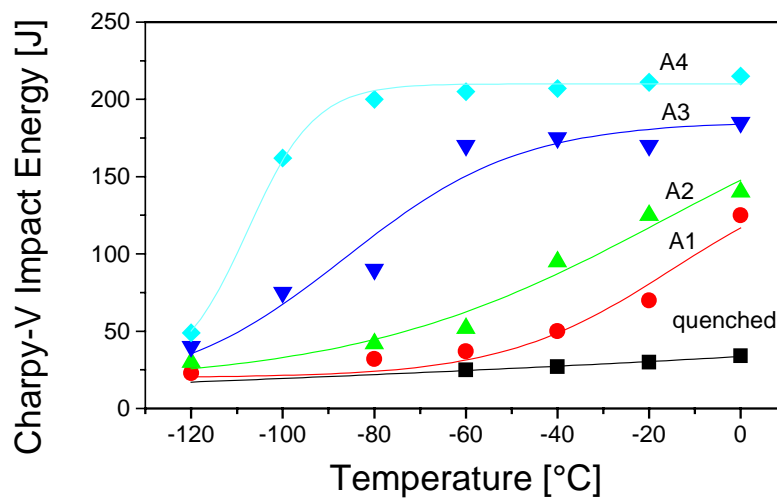


Fig. 5: Influence of increasing tempering temperatures on the Charpy impact transition of Dillimax 890 steel

The tempering conditions must be adapted to the particular chemical composition of the steel. The higher the toughness and strength requirements the closer gets the permitted range for the tempering conditions.

It has already been mentioned that the cooling rate achieved at mid thickness decreases with increasing plate thickness. Accordingly for thicker plates it is necessary to enhance the hardenability of the steel. Quenching a steel of insufficient hardenability would produce a plate, transforming to martensite only close to the surface but to a mixed softer microstructure at a certain distance below the surface. Homogeneous hardness through the thickness is achieved with a CE of 0.70 %, whereas a lower alloying composition with a CE of only 0.55 % results in a marked hardness gradient in the quenched condition (see figure 6).

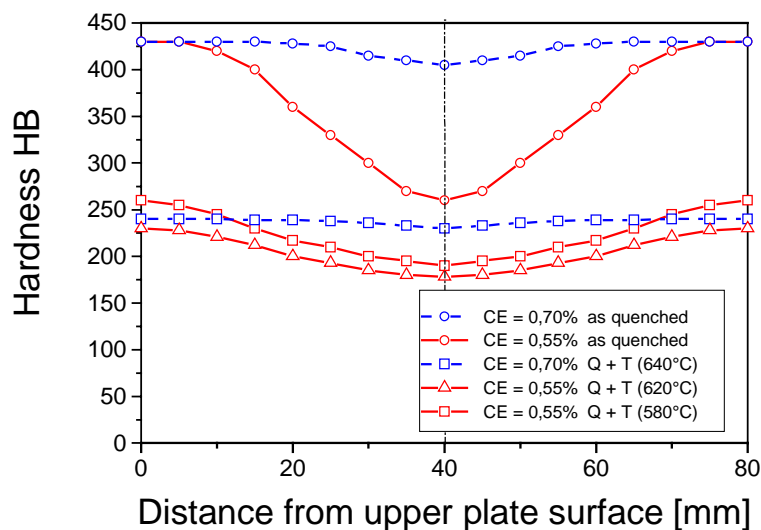


Fig. 6: Hardness distribution through the thickness of 80 mm plates produced from heats of appropriate (CE = 0.70 %) or insufficient (CE = 0.55 %) hardenability

Table 2 : Typical carbon equivalents of S690QL steel

Plate thickness	≤ 20	> 20 - 50	> 50 – 80	> 80 - 110	> 110 - 150
CE(IIW)	0.42	0.59	0.66	0.72	0.78
Pcm	0.26	0.31	0.32	0.34	0.35
CET	0.30	0.37	0.39	0.41	0.44

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

$$CET = C + (Mn+Mo)/10 + (Cu+Cr)/20 + Ni/60$$

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

After tempering the differences are becoming less pronounced than in the as quenched condition, but, may still lead to unsatisfactory properties particularly if upper bainite has developed. The necessary hardenability can be achieved by different combinations of alloying elements. The most effective ones are C, Mn, Mo, and Cr – of course the ones that also raise the carbon equivalents (see table 2) used to characterise

the weldability. A more difficult weldability must be overcome by precautions in welding. This means higher preheat and interpass temperature, the application of low hydrogen consumables and possibly soaking after welding for a more complete removal of residual hydrogen from the weld.

4. Thermomechanical rolled plates

The principle of TM-rolling has already been addressed. For a heavy deformation in rolling the steel at relatively low temperatures strong rolling equipment is a prerequisite. The hearts of the rolling mill in Dillingen are the two powerful rolling stands with up to 108 MN rolling force and a torque of 4.5 MNm. The dimensions of the larger stand allow to roll plates up to a width of 5.2 m. The ACC-equipment sizes of 4.5 m x 36 m. However, it needs more than just reduced rolling temperatures to produce TMCP plates of high quality. Many parameters have to be under control: slab reheating conditions, heavy deformation at individual rolling passes, temperature management until the final rolling temperature, start and finish cooling temperature, water flow rate and distribution in the ACC-equipment, to mention only the most important parameters.

Reproducible properties from plate to plate as shown in figure 7 require to adapt the rolling schedule to the final plate thickness. Homogeneous properties at all positions of the plate further need homogeneous temperatures through the process and even cooling. Special measures in the ACC-equipment like end and side masking, reducing the cooling intensity at the plate edges, improve the homogeneity of properties at all positions and result in good flatness and low residual stresses.

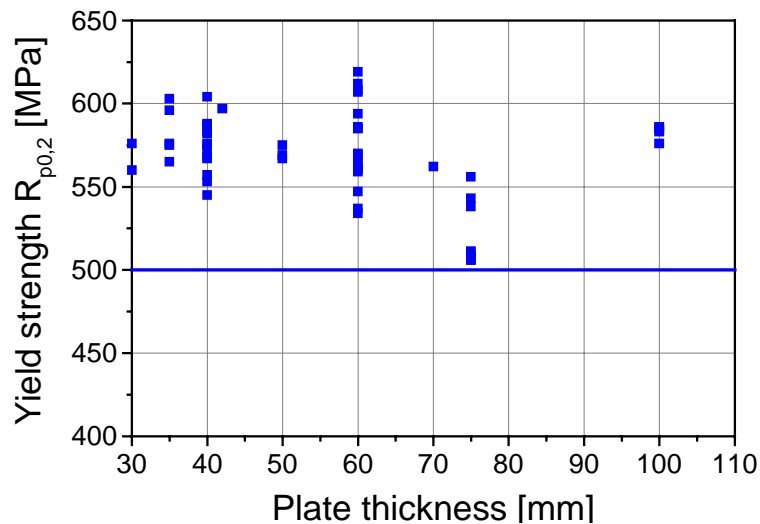


Fig. 7: Results of tensile tests for S500M steel: 0.2 % yield stress

Examples of an extremely fine grained microstructure are given in figure 8 prepared from a 75 mm thick 500 MPa-Y.S.- plate (S500TM) and Figure 9 shows the corresponding impact transition curve with excellent low temperature toughness as a result of the grain refinement. After successfully passing a material and weldability test program this steel was supplied to the Norwegian offshore industry since 2000 [6]. Today Dillinger Hütte has gained the production experience of several thousand tons of



S500TM for shipbuilding (Mayflower Resolution [7]), offshore (Valhall platform) and hydropower plant applications of plates ranging in thickness from 10 up to 100 mm.

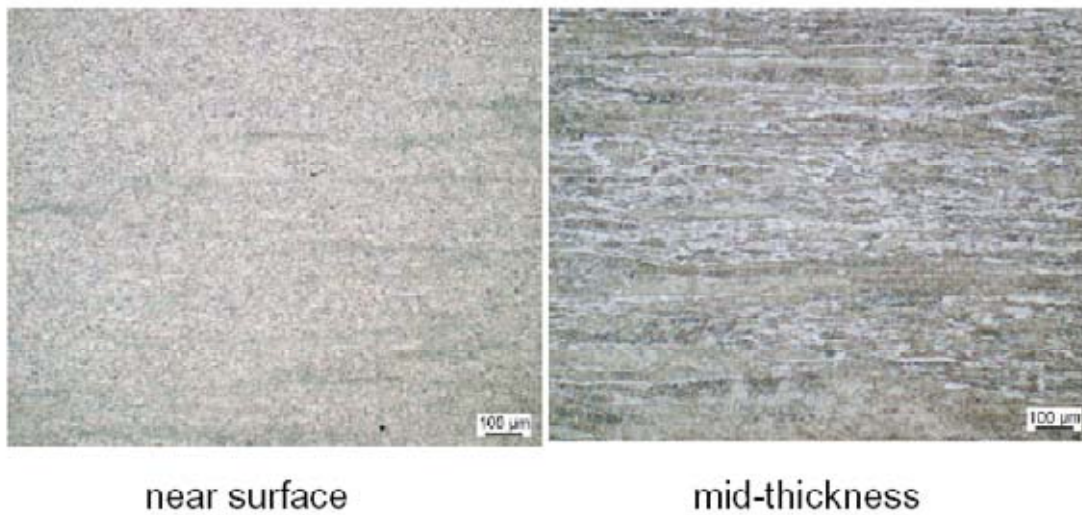


Fig. 8: Microstructures of a 75 mm thick thermomechanical rolled S500TM

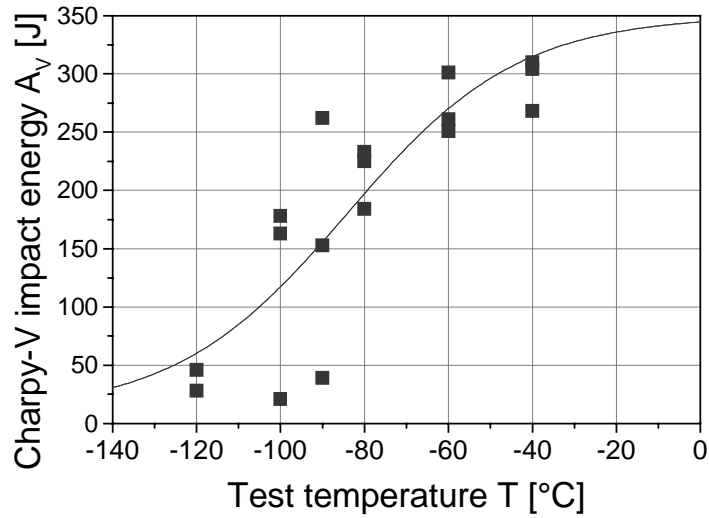


Fig. 9: Charpy V impact results of a 75 mm thick S500TM plate

The steel was mainly alloyed with manganese, nickel, copper and small microalloying with niobium. Some molybdenum was added to the heats from which the thicker plates were produced. The carbon content of this S500M could be kept below 0.08% leading to a P_{cm} value below 0.20 %. Thanks to the optimized chemical composition the steel was qualified for a wide range of welding conditions maintaining high level of impact and fracture toughness in the HAZ.

Recent improvements in the cooling equipment enable now to realize by TM-process even yield strengths of 700 MPa (DILLIMAX 700 M) in plate thickness up to 45 mm with a P_{cm} value less than 0.22%. A Charpy-V-transition curve of such a plate is plotted in figure 10.

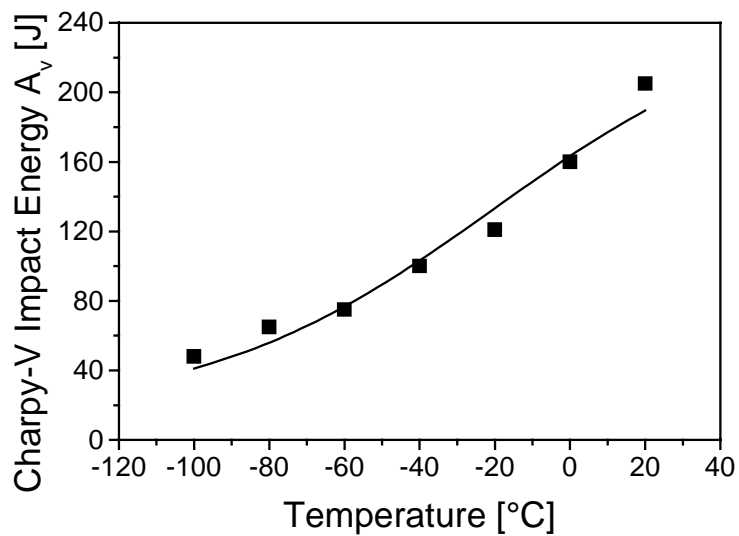


Fig. 10: Charpy-V-temperature-transition curve for an DILLIMAX 700 M steel. 45 mm (transverse values, average of three)

5. Welding

The weldability of structural steels of interest for the fabrication of penstock pipes shall be shortly addressed because of the relevance of welding to safety as well as erection cost.

The temperature-time cycles during welding have a significant effect on the mechanical properties of a welded joint. Generally the cooling time from 800°C to 500°C ($t_{8/5}$) is chosen to characterize the cooling conditions of an individual weld pass for the weld metal and the corresponding HAZ. Increasing heat input and interpass temperature leads to slower cooling and, hence, longer cooling time $t_{8/5}$. Knowing the welding parameters and geometry $t_{8/5}$ can be calculated (EN1011-2 : 2001 [8]).

The **HAZ hardness** determination is the only conventional test to measure local properties in a complex multipass weld. Other conventional tests like cross weld tensile test, bend or impact tests are methods where different areas of the HAZ or even base material, HAZ and weld metal contribute to the measured value. The hardness in the coarse grained zone of bead on plate welds, welded with varying heat input helps to determine the transformation behaviour of a certain steel composition. It is mainly determined by the chemical composition, the cooling speed and if applied, by a subsequent heat treatment. Diagrams showing the hardness as a function of the $t_{8/5}$ time, can be used to compare the transformation characteristics of different steels (figure 11).

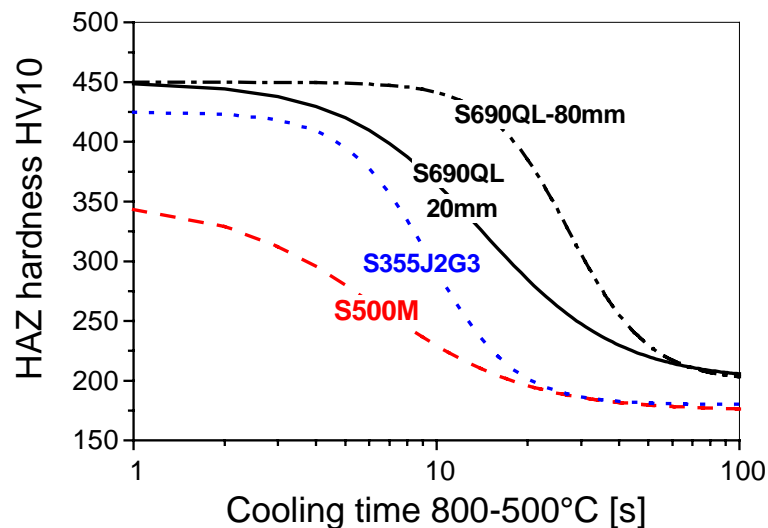


Fig. 11 : Hardness in the coarse grained HAZ as a function of weld cooling time ($t_{8/5}$) for some structural steels in the as welded condition

To achieve satisfactory weld metal properties the welding parameters must be limited with increasing yield strength. Acceptable properties for an S690 steel are normally obtained with cooling times between 6 s and 20 s. Within this cooling range



the coarse grained HAZ a 80 mm thick S690Q steel transforms mainly into martensite with a corresponding hardness above 400 HV. For the same conditions the 20 mm S690Q with a lower alloy content, transforms into a mixture of martensite and bainite content having a hardness of about 350 HV. Unlike the S690Q steels, the S500M produces for all usual welding conditions a HAZ hardness below 300 HV. This is due to the much lower carbon content (0.07% instead of 0.17%) combined with a low alloying content. It can be seen that the hardenability of this S500M steel is even below the one of a conventional normalized S355J2G3 (0.18%C - 1.50%Mn) steel.

Table 2 : Typical carbon equivalents characterising the hardenability (CE) and the HAZ cold cracking susceptibility (CET, Pcm) for some structural steels

	CE	CET	Pcm
S355J2G3 80mm	0.44	0.33	0.25
S500M 50mm	0.42	0.26	0.18
S690QL 20mm	0.44	0.29	0.24
S690QL 80mm	0.70	0.39	0.32



Fig. 12.1 : Hydrogen induced cracks in the weld metal of a submerged arc weld of a S690Q steel



Fig. 12.2 : Positions of the cracks in the weld metal, polished surface etched in 3% nital

One example for **hydrogen induced cracking** of an S690Q weld is shown in figure 12. On the polished surface cracks, as well transverse as parallel to the welding direction are present. On the photo the cracks appear bright. After etching it became

evident (figure 12.2) that the defects are located in the weld metal in the center of individual welding passes or transverse in the weld metal. The cracks were arrested in the HAZ at the fusion line. How can this behaviour be explained? The welding consumables that produce tensile properties overmatching the ones of S690Q need a relatively high alloying content. A combination of 1-2.5 % nickel, 0.5-1.5% of chromium and about 0.5% molybdenum is here typical. Due to this chemical composition and its as cast microstructure weld metals for steels of 690 MPa yield strength are often more susceptible to hydrogen induced cold cracking than the HAZ of the high strength steels. In order to avoid cracking, preheat and interpass temperature must then be adapted to the weld metal. A steel with reduced carbon equivalent would not allow to drop these the precautions in welding. Consequently, high strength parent material with reduced carbon equivalents, as achieved by TM-rolling, need essentially the same precautions as the higher alloyed QT steel.

In order to produce sufficiently high strength properties in the weld, the heat input must be restricted to approximately 2 kJ/mm. Thereby the deposition rates and the welding economy are reduced and together with the precautions, the welding time may increase in spite of the reduced weld volume needed for higher strength pipes. Figure 13 compares applicable working ranges for different structural steels. The lower limit of the temperature is set for the avoidance of cold cracking, the upper limit for the heat input and interpass temperature are introduced by gaining sufficient tensile and toughness properties.

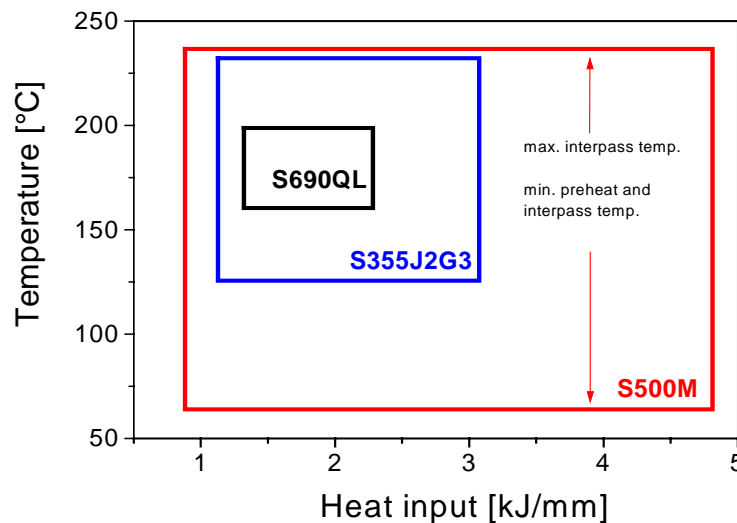


Fig. 13 : Typical working ranges for welding of structural steels in plate thickness providing the same load bearing capacity (S355J2G3-80 mm, S500M-50 mm, S690QL-30 mm)

6. Conclusion

The paper gave an overview of a range of structural steels. The different supply conditions were explained and some results marking the state of material development were shown. Steel plates up to a yield stress of 690 MPa and in special cases even 890



MPa were used for penstock pipes. However, also somewhat lower strength grades, such as S500TM may offer considerable advantages due to excellent fabrication properties. The choice of the "best" steel for the pipework in a hydropower plant is project depending. Head height, pipe diameter, geology, seismic activity and from the economic point of view: cost of materials, processing and installation and also inspection intervals must be considered.

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