Production and progress work of plates for pipes with strength level of X80 and above

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Abstract

Plates for pipes with strength level of grade X80 can be produced nowadays with the same reliability and reproducibility as lower grades. This has to be seen as a consequence of the application of sophisticated steel- and plate-making route incorporating Thermo-Mechanical Controlled Process (TMCP) and a tight control of all production steps and parameters. Increased thickness or reduced design temperatures, e.g. for very cold regions, or even the combination of both are considered for upcoming linepipe projects. In order to be prepared for such future demands full scale production trials were performed. These optimistic results are shown.

Dillinger Huettenwerke developed in subsequent stages plates to produce pipes in grade X100. The different approaches in respect of steel analysis and cooling conditions resulting in different property profiles are pointed out. Grade X100 plate material is in principle available in a specific range of thickness, plate width and design temperature. Outlook for progress work to extent the feasibility for steel grade X100 is also given.

keywords: X80, X90, X100, analysis, cooling process, thickness, design temperature

Introduction

In the gas industry there is a serious demand to improve the economic benefits by an optimization of the design of the pipeline. A decisive factor to enlarge the quantities of gas over long distances is the enhancement of the pressure. Consequentially higher strength or thicker materials are prospected.

Although grade X80 material is available since some years [1] only few pipelines being installed using longitudinally SAW (Submerged-Arc-Welded) pipe of grade X80. However it can be seen that the benefits of grade X80 is nowadays more and more considered and applied. The paper will point out results of recent orders in thickness of 14.4 and 25.4mm with grade X80 or similar. Current projects are envisaging increased thickness, e.g. to increase the pressure, or reduced design temperatures, e.g. for very cold regions, or even the combination of both. Another challenging application where increased thickness are targeted is X80 for Offshore in very deep waters. Results of full scale production trials, performed in order to be prepared for such future demands, are shown.

Further cost savings can be expected by the application of ultra high grade steels like grade X100 especially for longer distance pipelines [2]. However the demanded development of grade X100 can be viewed as a quantum leap for the steelmaker, pipemill, designer, contractor and user alike [3]. The paper critically outlines different approaches to produce plates for pipes in grade X100. Actual state and perspectives for a further optimization of the property profile are pointed out.

One fundamental precondition to produce high and ultra high strength high toughness steels are state of the art production facilities. Another basic condition are optimized production concepts and parameters. Both include the complete production process, i.e. the steel- and plate-making. The paper will solely focus on the plate-making process.

TMCP, the rolling plus cooling process

Besides general aspects like dimension, the production of a plate is focussed to obtain a specified property profile. The achieved properties expressed e.g. by tensile, CVN (Charpy V Notch) impact or BDWT (Battelle Drop Weight Tear) test, are a function of the steel- and plate-making parameters. All these parameters have to be defined taking into account their metallurgical and interdependent mechanisms. For fixed steel making parameters like steel composition and casting condition, the properties of a plate produced by TMCP (Thermo-Mechanical Controlled Process) are achieved by a special time and temperature sequence. This incorporates the reheating of the slab to specific temperatures, the rolling to successive thickness with specific reductions at defined temperatures interrupted by cooling periods (Figure 1a). The cooling after finishing rolling can be performed on ambient air or in water down to specific final cooling temperature (followed by cooling on ambient air) with specific cooling rate (Figure 1b).

In case of high strength or even ultra high strength combined with high toughness at low temperatures and good weldability the cooling with water plays an essential role. To exploit different mechanisms to best achieve the specified property profile various cooling variants can be applied (Figure 2). In the case of ACC (Accelerated cooling), cooling as shown in Figure 2a is used and results in cooling with ideal cooling rate. In the case of DQ (Direct Quenching) fastest possible cooling of the surface, similar to conventional quenching, is applied. The center of the plate is also cooled to below the martensite-start temperature by means of continuation of cooling (Figure 2b). DQST (DQ + Self Tempering) means that the center heat still present is exploited after an extremely short cooling time and self-tempering is achieved (Figure 2c). HACC (Heavy ACC) is a special variant of the classical ACC but with lower final cooling temperature and somewhat higher cooling rate.

Common to all the process variants and particularly true of the more recent variants is the role of process control and quality assurance in the achievement of all the specified requirements. In practice, a tolerance range ("window") of property figures is in fact permitted, but must be achieved with statistical certainty, i.e. repeatable. All cases demands good knowledge of the underlying metallurgical interrelationships and adjustment of all process parameters with defined standard deviations. Both are essential during steel-making in the steelplant, i.e. adherence to the target composition, and also during the TMCP rolling process, including cooling, and on-line monitoring and approval systems.

Production of grade X80

Figure 3 represents distribution curves for tensile and CVN test results in transverse direction for plates produced in 14.4mm thickness of grade L555MB. Grade L555MB requires according to Euronorm EN10208 a minimum YS of 555N/mm² (MPa) and TS of 625N/mm² (MPa). The grade is therefore comparable to grade X80, except for elongation. Grade L555MB requires on pipe a more difficult to fulfill minimum proportional elongation (A_5) of 18%, whereas grade X80 specifies a minimum elongation A2" of 21%. The project related CVN testing temperature on plate was at -20°C with a minimum requirement of 150J. The plates were produced to form pipes in diameter of 48" (~1219mm). Due to the low thickness in combination with the high plate width, a plain TM rolling schedule -without ACC- was applied to prevent any flatness related problems. A CMnNbTi based steel with alloying of about 0.20% Mo was used resulting in a carbon equivalent CE_{IIW} of about 0.44%. The figure demonstrates that the requirements are comfortable met. The standard deviations of 15N/mm² (MPa) for the YS and TS and 1.4% for proportional elongation (A_5) are noticeable.

For higher plate thickness the application of ACC is inevitable to keep sufficient low carbon equivalent. Figure 4 gives frequencies for tensile and CVN test results in transverse direction for plates produced in 25.4mm thickness of grade X80. CVN test was required on plate in mid thickness position at -30°C with a minimum of 50J. Again a CMnNbTi based steel with a carbon equivalent CE_{IIW} of about 0.44% was used. That means a steel with the same carbon equivalent as for the steel in 14.4mm, as explained above, was used. To meet the specified property profile TM rolling plus HACCI process was applied. Again the property profile is comfortable met and achieved in a tight scatter band.

Comparing the presented results of grade X80 with lower grades [4, 5] it can be concluded that X80 can be produced with the same reliability and reproducibility as grades with lower strength levels. Grade X80 in thickness up to 25mm (1") can be viewed meanwhile as standard production.

Extension of grade X80 to higher thickness and lower design temperature

Thicker plates are more difficult to produce because of lower cooling rates of the core and lower deformation ratios during TMCP. Therefore the extension of steel grades to higher thickness requires a more sophisticated and adapted steel and plate production process. Primarily for thicker plates the benefit of the application of higher slab thickness (up to 400mm) on CVN impact and BDWTT properties has been demonstrated [6, 7]. By the application of higher slab thickness the deformation ratios at the different rolling stages can be maintained sufficiently high even for higher final thickness. During cooling of the plate enriched, i.e. segregated areas are transforming at a lower temperature. Carbon diffusion from already transformed to those segregated areas can lead to an additional increase in carbon content resulting in local less tough constituents. The carbon content and consequentially the microstructure in the segregated areas is among other things influenced by the carbon content obtained after solidification and the cooling rate during the plate making process. Therefore for thicker plate it is of basic principle to be in a position, as Dillinger Huettenwerke is, to minimize anymore the segregation level during solidification process by appropriate casting equipment [8]. In addition cooling equipment is available to get effectual influence of the cooling during TMCP be it to reduce carbon diffusion to segregated areas or to achieve sufficiently high fraction of bainitic microstructure [9].

Figure 5 compares the CVN impact test results at -60°C with BDWTT shear areas at -40°C. The investigation was performed on grade X80 with a thickness of 33.7mm. A steel with alloying of Mo resulting in a carbon equivalent CE_{IIW} of about 0.45% was used. Final rolling and cooling temperatures and cooling rates are varied to investigate the influence on CVN and BDWTT results. There is no unique correlation between CVN impact toughness and BDWTT shear area. In particular the best BDWTT shear areas are obtained in the area of lower CVN toughness. That has already been shown for lower grades [6]. Concluding further optimization must be focused to obtain best balanced properties in respect of CVN toughness and BDWTT shear area. As shown in Figure 5 best balanced properties are achieved with a concept resulting in about 300J in CVN test at -60°C and about 80%shear in BDWTT at -40°C. As the results on BDWTT were not yet satisfied further investigation and optimization trials have been performed on plates in thickness of 32mm. A CMnNbTi based steel was used. The alloying concept was upgraded by addition of Ni of about 0.20%. In addition slab reheating temperature was reduced and deformation ratios above and below recrystallisation stop temperature was mutually balanced. Figure 6 illustrates the transition curves on CVN toughness and BDWTT shear area obtained on these steels. Even for very low testing temperatures worth mentioning results are achieved. BDWTT shear areas of ≥ 85% are obtained for temperatures ≥ -60°C and CVN toughness level above 200J is maintained down to temperatures of -100°C. Although the results must be verified during mass production these give some confidence to be prepared for future extraordinary requirements.

Development stages of grade X100

The development of grade X100 has taken up as a challenge and provoked substantial developments. In particular development in steel making, plate rolling and cooling facilities as well as in advanced design of the steel analysis and process parameters were necessary [6 - 9]. Some basis of grade X80 has been maintained for the development of grade X100. NbTi microalloying is essential to achieve a very fine microstructure but also to obtain precipitation strengthening. Mn content must be sufficiently high as it suppresses the pearlite formation. Carbon content and equivalent must be kept low enough to maintain adequate weldability. However it is obviously that the fraction of bainite must be increased and optimized. As the addition of alloying element must be limited the key factors are the cooling parameters.

During the development stages of plates for pipes of grade X100 Dillinger Huettenwerke casted and investigated different steel concepts (Table I). All steels were produced with lowest contents of P, S and O, are vacuum and Ca treated, received special cleanness treatment and are microalloyed with approximately 0.05% Nb and 0.02% Ti. To prevent accumulation of inclusions all the slabs are casted on a fully vertical type caster with bending and straightening after complete solidification. Selective measures are performed to minimize segregation during casting [8]. The paper will point out the results of slabs rolled to plate thickness between 15 and 20mm. The rolling conditions are very similar for all presented results. However different cooling variants, as explained above, are applied. All the cooling variants were achieved with the same cooling equipment namely the MULPIC (Multi purpose interrupted cooling) device [9]. Plates of steel concept A, C, D and E were formed to pipes by Europipe. Additional and further investigations were performed on those pipes and some pipes were used to carry out full scale burst tests [10 - 12]. For the full scale burst tests different toughness levels at ambient temperature were prepared on purpose in order to evaluate crack arrest behavior.

steel concept: medium carbon - low carbon equivalent

Figure 7 shows the tensile and yield strength and Figure 8 the CVN toughness result at -20°C for steel concepts A, B and F obtained for different cooling variants. For YS and TS requirements for grade X90 and X100 are included. The requirements are derived by an extrapolation of the API 5L specification. All the steels have a low carbon equivalent and a medium carbon content. Steel A is alloyed with MoNi, steel B with CuNi. Steel F have no additional alloying. Strength level of X100 can be clearly achieved for cooling variants with sufficient low final cooling temperature in combination with high cooling rates. This is true even for the leanest steel without additional alloying, i.e. for steel F. However toughness level of steel F is noticeable lower than for steel A and B. The highest toughness levels for steel A and B are obtained for the DQST II cooling variant. Low carbon equivalents are in general beneficial for welding aspects. But it is worth mentioning that the concepts of steel A, B and F can lead to a too clear softening in the HAZ [10, 13, 14].

steel concept: medium carbon - high carbon equivalent

Steel concepts D and E have compared to steel concepts A and B additional amount of alloying elements and consequently higher carbon equivalents. Strength properties of grade X100 are obtained already with moderate cooling conditions, i.e. with cooling process HACCI (Figure 9). The toughness level for cooling process HACCI was quite appreciable (Figure 10). However it must be noted that to have a safe production in respect of strength properties, cooling process more close to HACCII, with less toughness values, would need to be applied. Moreover the steel analysis of concepts D and E incorporates disadvantages on weldability [10, 14] . It should be added that in case of DQ even grade X120 was obtained, but the toughness level was just above 150J.

steel concept: low carbon - medium carbon equivalent

In comparison with steel concepts D and E the concept C makes use of a lower carbon equivalent. That is achieved mainly by a reduction of the carbon content. Therefore that concept ensures fully satisfactory field weldability despite the alloying of Mo and Ni resulting in a medium carbon equivalent [10, 12]. Figure 11 and Figure 12 are showing the tensile and yield strength and CVN toughness results at -20°C obtained for different cooling variants for the steel concept C. Process HACCII gives tensile properties sufficient for grade X100. Grade X90 could be achieved even by the application of the classical ACC process. The obtained toughness values are clearly above the other steel concepts and are remarkable. Another advantage is that the properties, compared with the other steel concepts, are less sensitive to a variation in cooling conditions. Therefore consistency in properties is also ameliorated. It should be complemented that the proportional elongations (A_5) are at about 16-17% and the transition temperature for 85% shear in BDWTT is at about -30°C. Steel concept C is the currently preferred approach to produce plates for pipes in grade X100 with design temperature at 0°C. Plate material is feasible up to a thickness of 20mm and in a plate width to make pipe with a diameter up to 36" (~914mm).

Outlook for progress work for further development of grade X100

The development of grade X100 was up to now mainly focussed to reach requirements for design temperature at about 0°C. The concepts were optimized to produce thickness up to 20mm and pipe diameter up to 36" (~914mm). Actually there is a serious demand to make use of grade X100 at clearly lower design temperatures and higher pipe diameter. Figure 13 gives the CVN transition curves in transverse direction for grade X90 and X100 (steel concept C, plate thickness 17 mm). The cooling conditions were adapted to produce the respective grade. The difference in upper shelf itself as well as transition temperature at upper shelf energy is obvious for both grades. Indeed the transition curve for grade X100 on plate is already at an appreciable level. But this is not enough to safely meet requirement for brittle fracture (e.g. to be tested at 20K below design temperature with CVN ≥ 150J) and crack arrest (e.g. at design temperature with CVN ≥ 260J) at very low design temperature (e.g. at -25°C) as a deterioration from plate to the pipe and a certain scattering during mass production must be taken into account. That means progress work is required to improve toughness values without impairment of the accompanied properties.

Current investigations will look for a further optimization starting from steel concept C. For toughness it is desirable to make use of a cooling process close to HACCI. But also to produce plates in higher width, i.e. for higher pipe diameter (e.g. 48" (~1219mm)), a cooling process with higher final cooling temperature is preferred to prevent plate flatness related problems. In order to meet and stabilize the strength properties for cooling variant HACCI, the carbon equivalent will be increased. However it has been demonstrated above that it is substantial important to keep the carbon content at a low level. Therefore the carbon equivalent will be increased by additional alloying. In addition the rolling parameters, like reheating temperature, will be optimized with regard to a further gain in toughness.

Another aspect to be discussed with designers is the requirement on TS as grade X100 is not yet included in the API Specification. Figure 11 demonstrates that in case of a difference between minimum TS and YS requirement of 70N/mm² (MPa), as for grade X80, the TS is more at the borderline. Therefore a reduction of the minimum TS requirement down to 750 or 740 N/mm² (MPa) could be simplify the further development.

Summary

The paper has compiled the actual status for grades of X80 and X100 from a point of view of a plate manufacturer. An outlook for a possible extension of feasibility and further development is also given. It can be summarized:

1. Plates for gas transporting pipes with strength level of grade X80 are nowadays available up to 25.4mm (1") and can be produced with the same reliability and reproducibility as lower grades.
2. Extension of grade X80 to higher plate thickness even in combination with very low design temperature is practicable.
3. During development stages of grade X100 different approaches has been applied. The current preferred approach to produce plates for pipes with design temperature of 0°C makes use of a low carbon content in combination with a medium carbon equivalent. So called HACCII process is applied to produce these plates. Plates in thickness up to 20mm for pipe diameter up to 36" (~914mm) has been produced with adequate properties.
4. Further development is required and started to extent grade X100 to higher thickness, higher pipe diameter and lower design temperatures.

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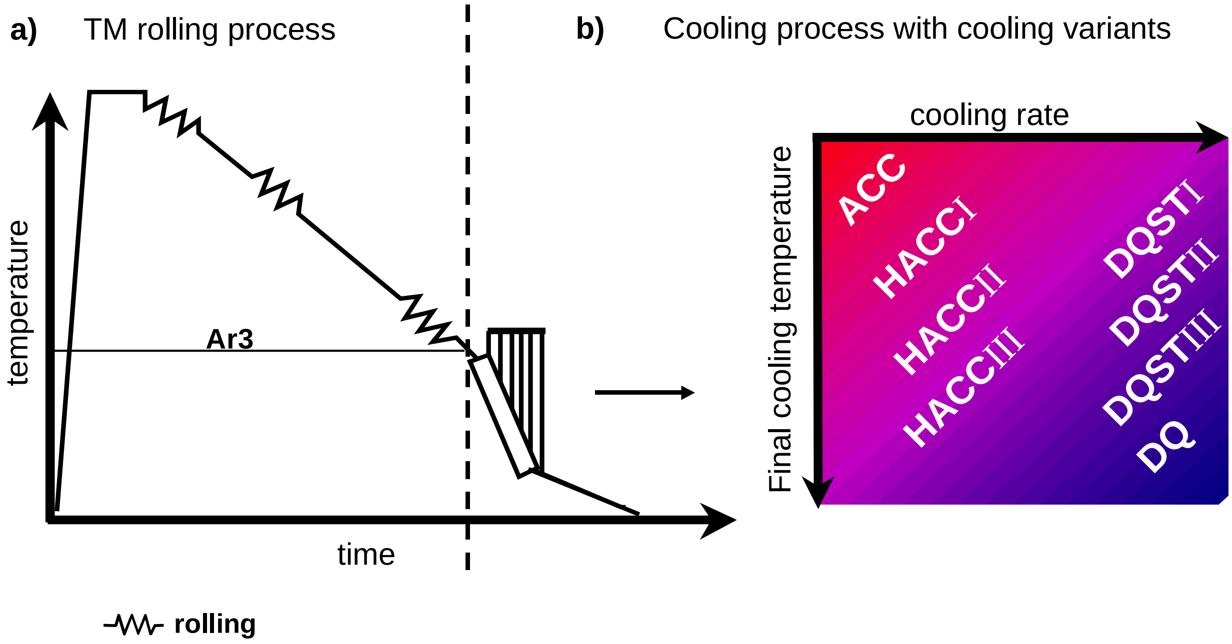
Tables and Figures

steel	C	Si	Mn	Cu	Mo	Ni	CE_{IIW}	p_{cm}
A	0.07	0.30	1.90	-	0.17	0.20	0.44	0.19
B	0.09	0.30	1.88	0.13	-	0.14	0.44	0.20
C	0.06	0.35	1.92	-	0.30	0.25	0.46	0.19
D	0.07	0.30	1.95	0.20	0.17	0.33	0.48	0.20
E	0.08	0.30	1.93	0.20	0.25	0.24	0.49	0.22
F	0.08	0.33	1.93	-	-	-	0.42	0.20

Table I: Analysis concepts (in wt.-%) of NbTi microalloyed steels for development of grade X100



ACC = **A**ccelerated **C**ooling, **HACC** = **H**eavy **ACC**, **DQ** = **D**irect **Q**uenching, **DQST** = **D**irect **Q**uenching and **S**elf-**T**empering

Figure 1: Schematic diagram of a) TM rolling process with b) Cooling process with cooling variants

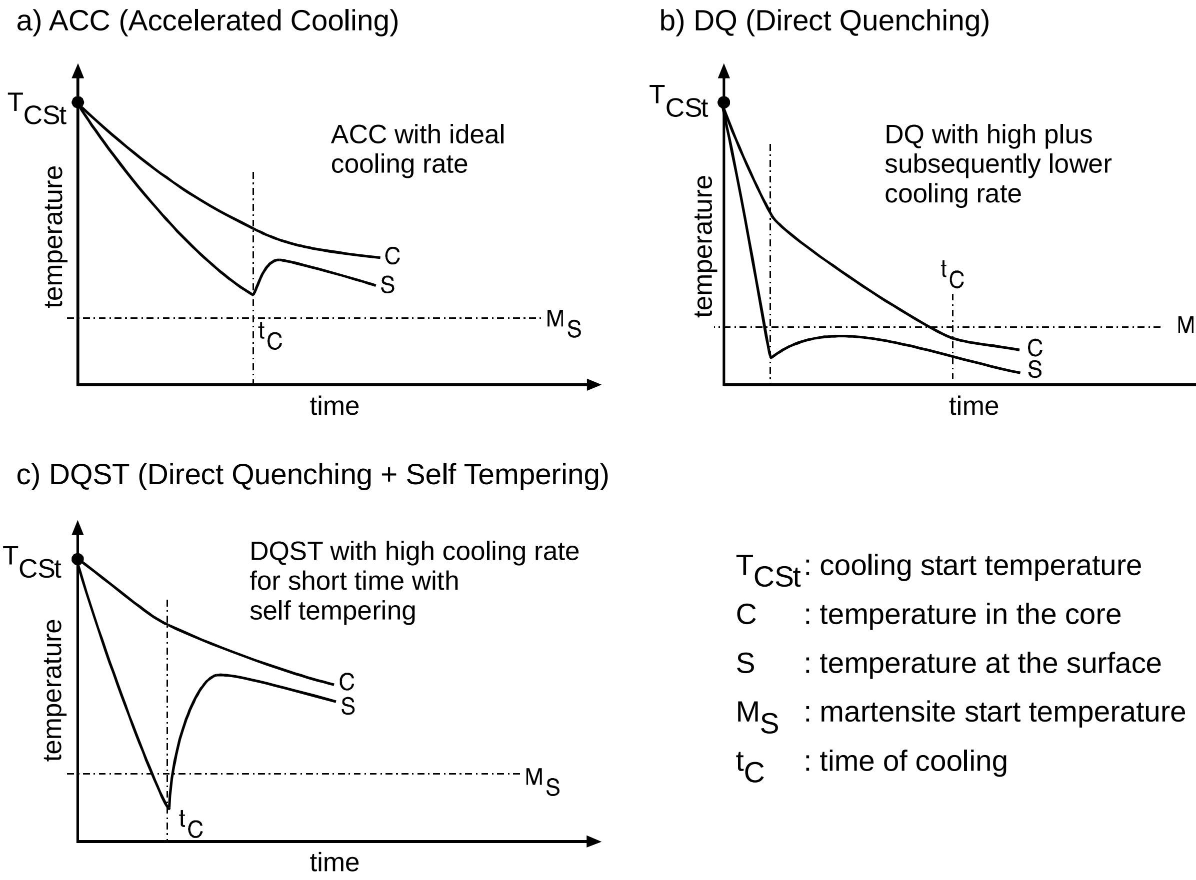


Figure 2: Design of cooling process - aspects and variants

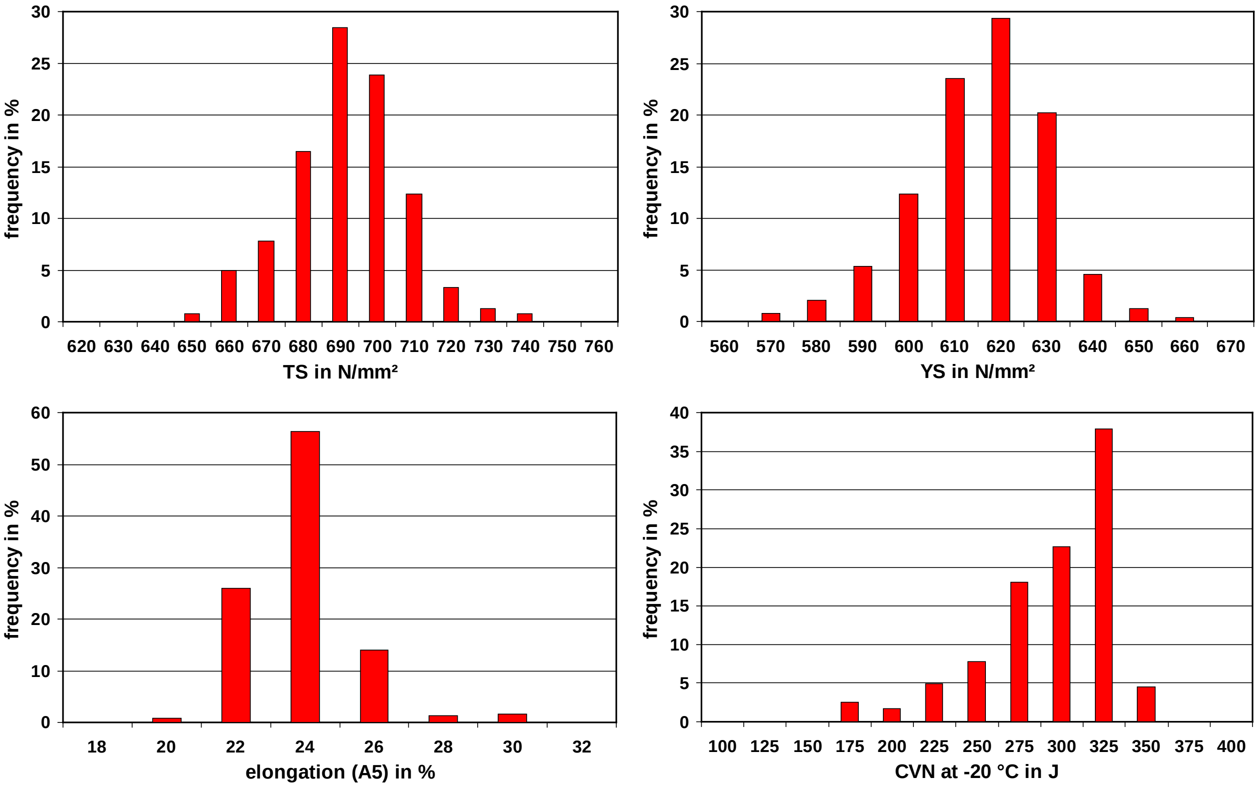


Figure 3: Tensile and CVN impact test results in transverse direction of 14.4mm grade L555MB (X80)

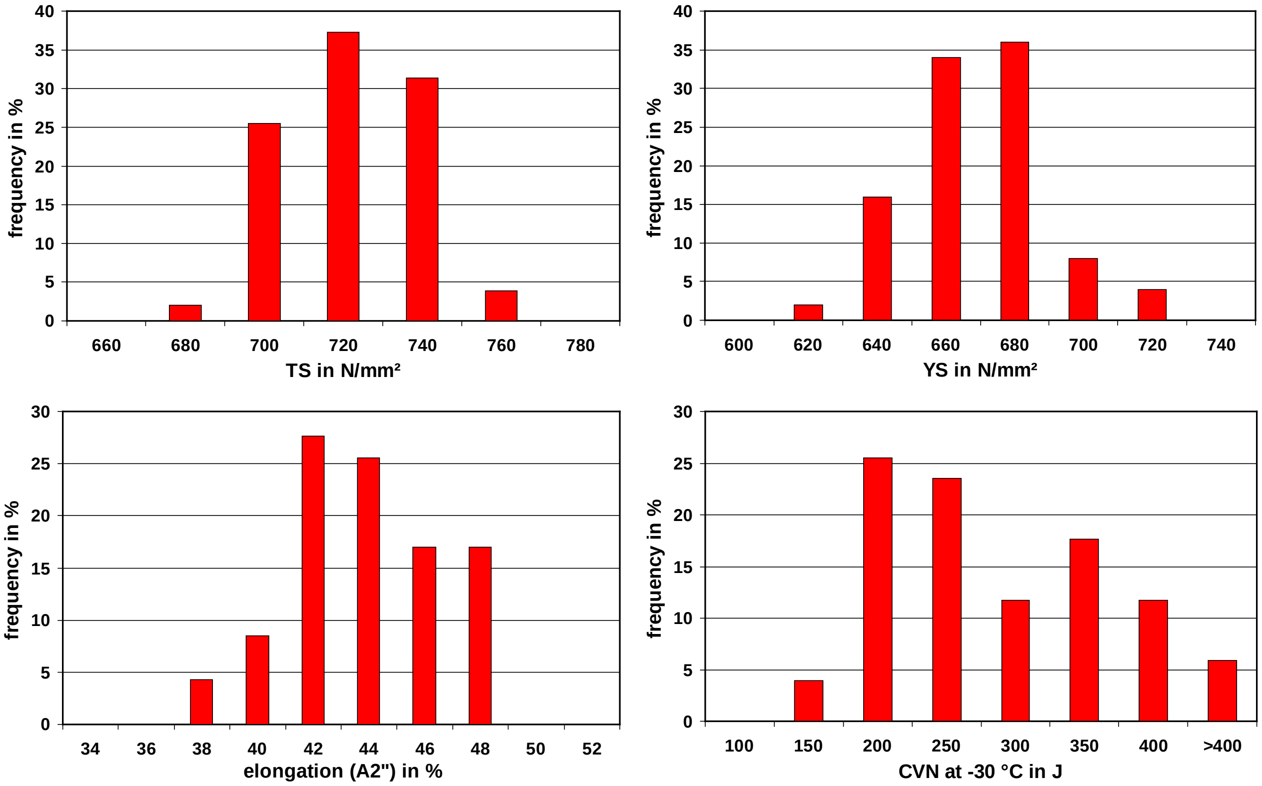


Figure 4: Tensile and CVN impact test results in transverse direction of 25.4mm grade X80

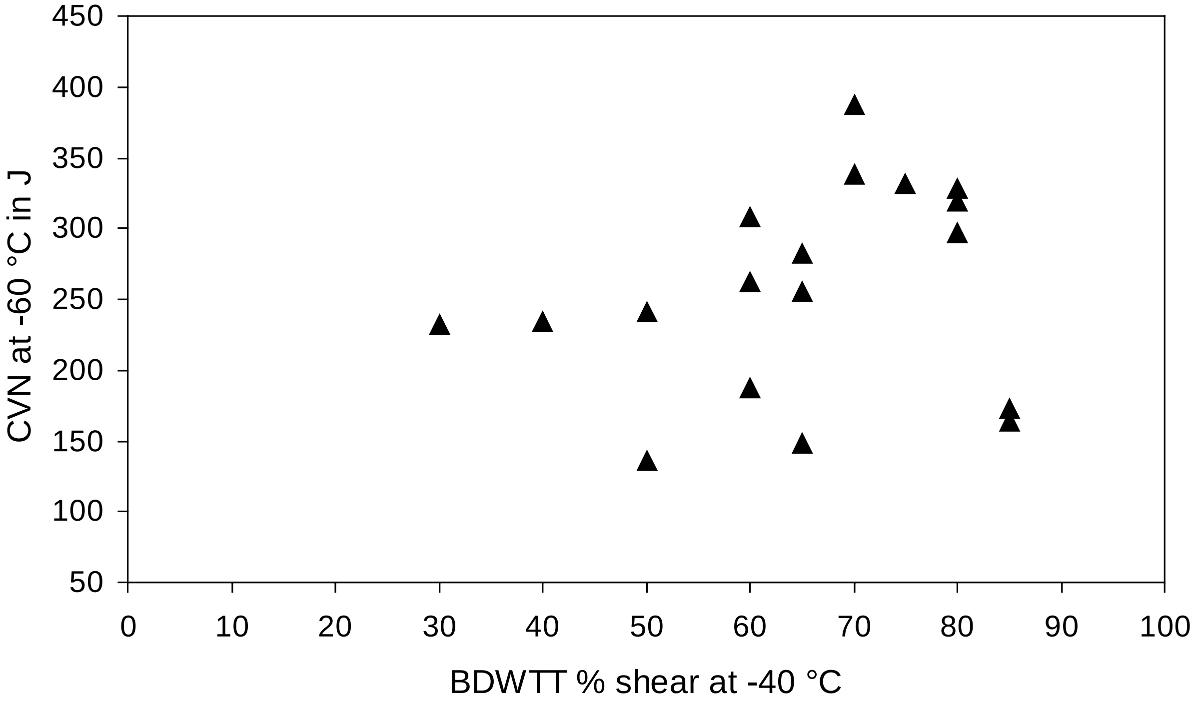


Figure 5: CVN impact test results in quarter thickness and BDWTT in transverse direction of grade X80 in 33.7mm achieved by different rolling and cooling conditions

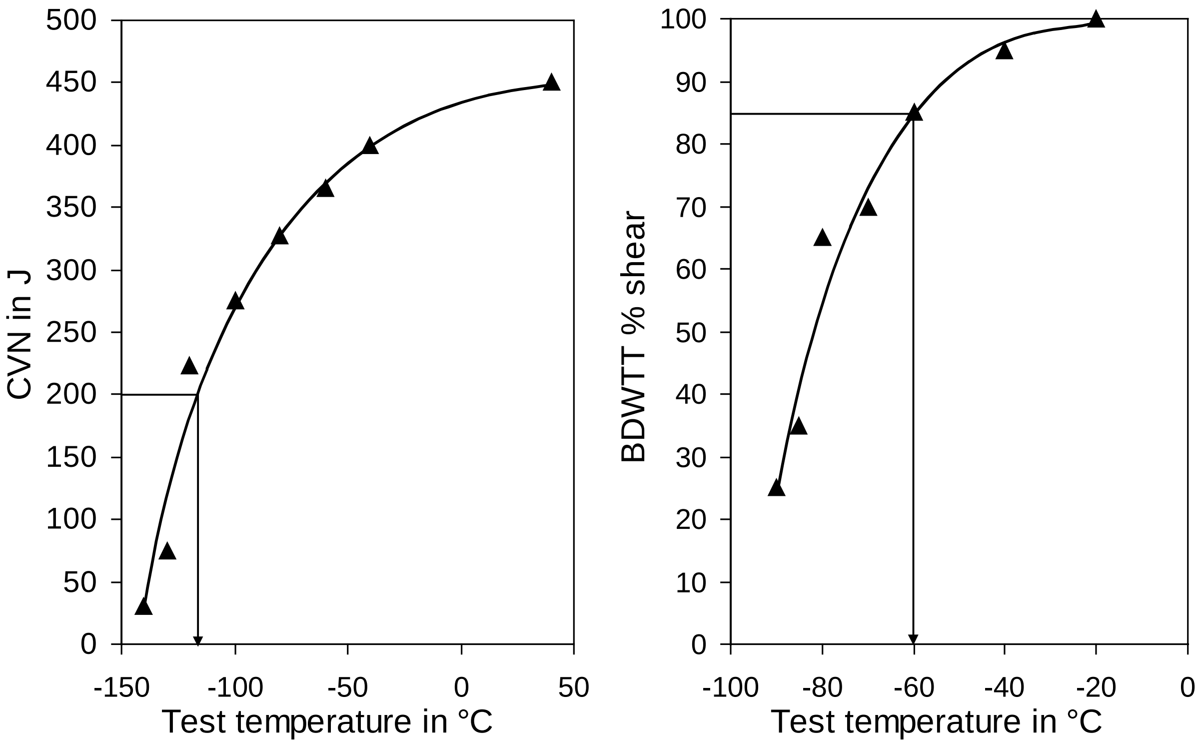


Figure 6: CVN impact test results in quarter thickness and BDWTT transition curves in transverse direction for optimized and balanced concept achieved on X80 in 32mm

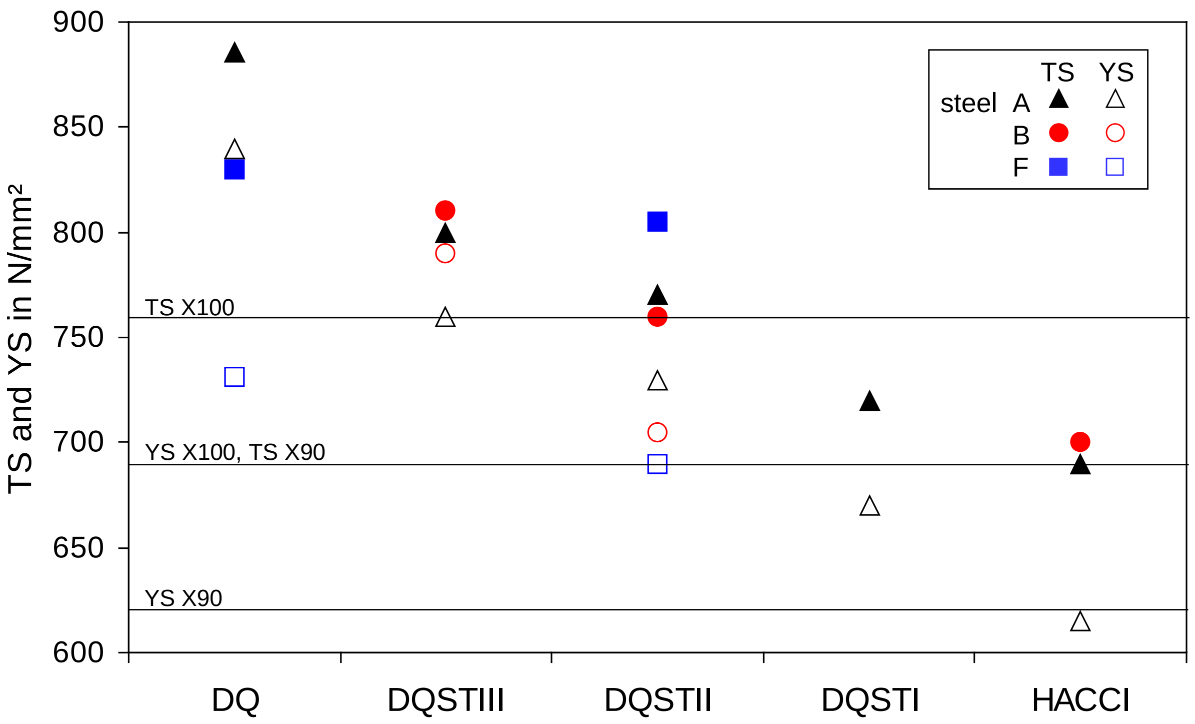


Figure 7: Tensile and yield strength in transverse direction for different cooling variants for steel concepts A, B and F (medium carbon - low carbon equivalent, plate thickness 15mm)

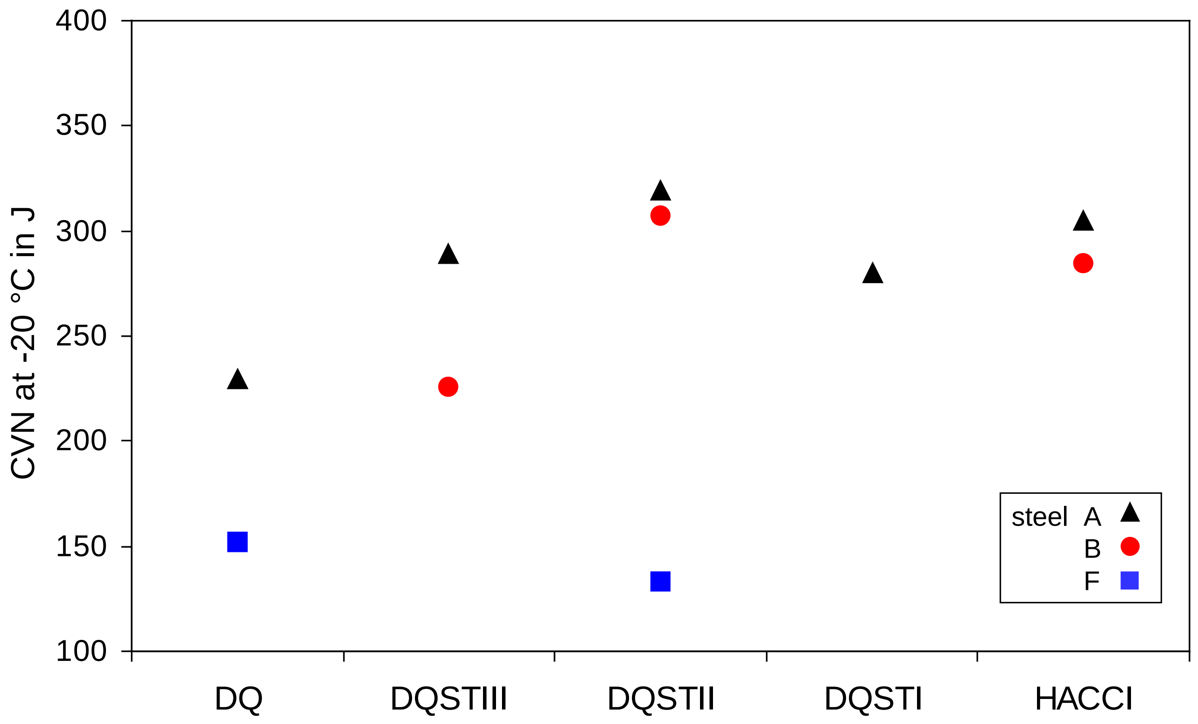


Figure 8: CVN impact test results in transverse direction for different cooling variants for steel concepts A, B and F (medium carbon - low carbon equivalent, plate thickness 15mm)

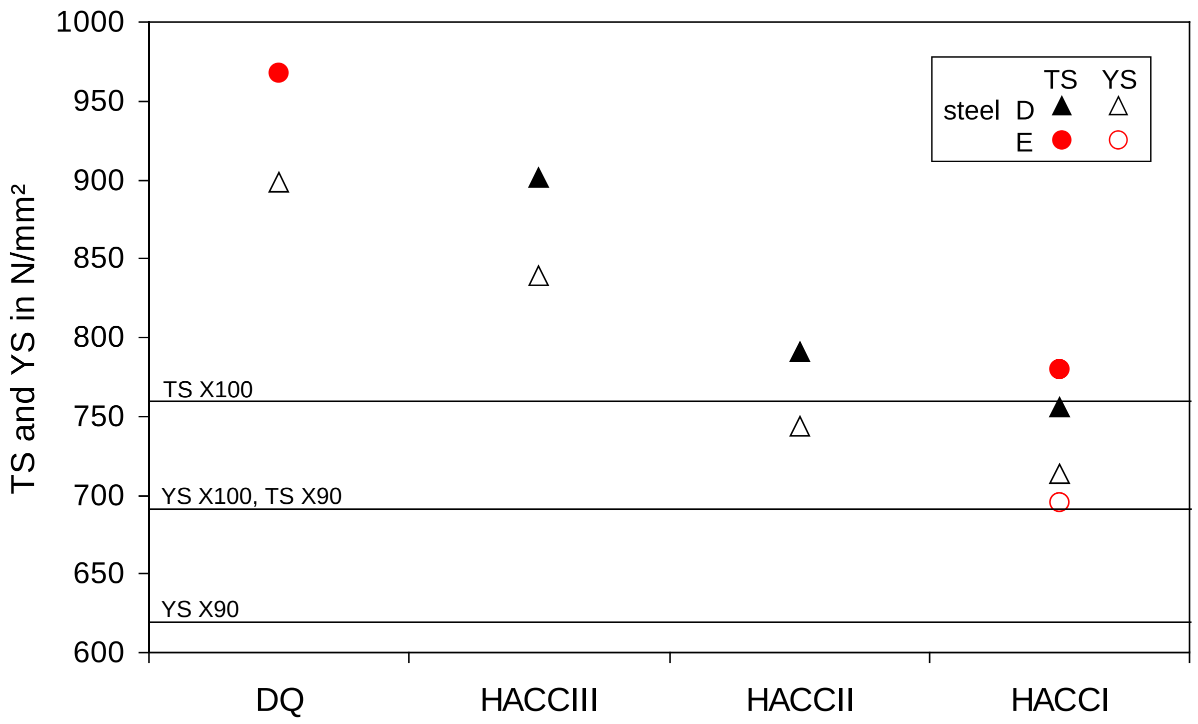


Figure 9: Tensile and yield strength in transverse direction for different cooling variants for steel concepts D and E (medium carbon - high carbon equivalent, plate thickness 19 and 20mm)

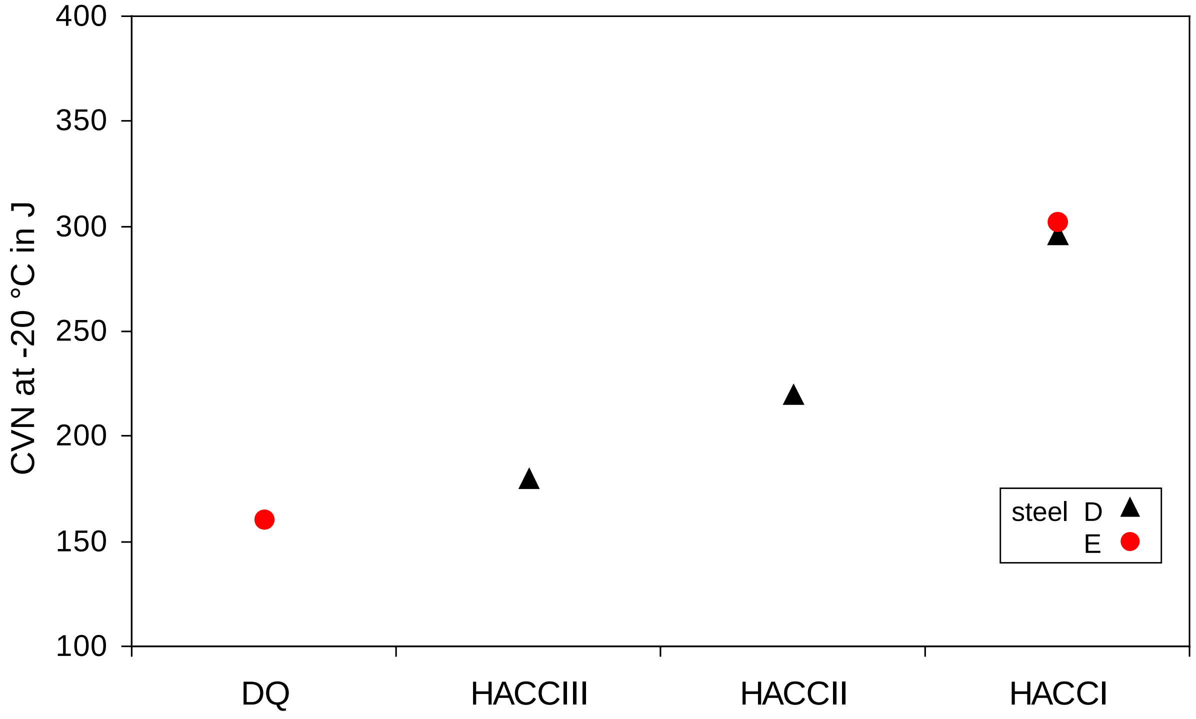


Figure 10: CVN impact test results in transverse direction for different cooling variants for steel concepts D and E (medium carbon - high carbon equivalent, plate thickness 19 and 20mm)

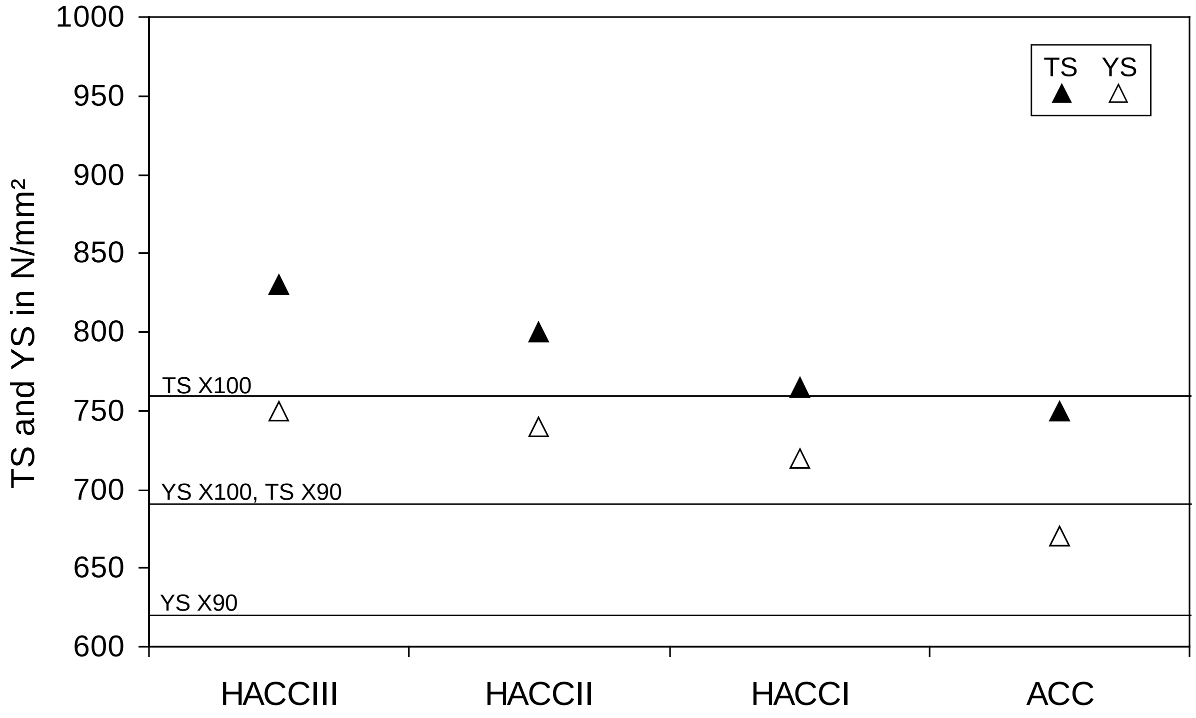


Figure 11: Tensile and yield strength in transverse direction for different cooling variants for steel concept C (low carbon - medium carbon equivalent, plate thickness 17mm)

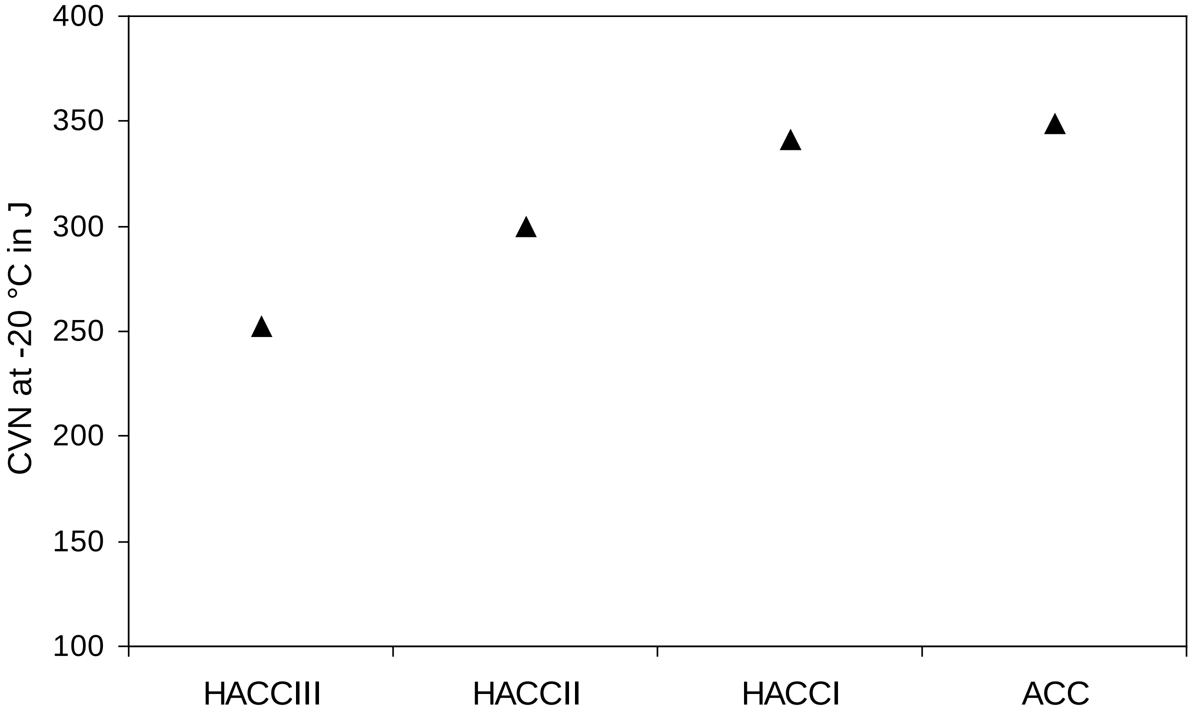


Figure 12: CVN impact test results in transverse direction for different cooling variants for steel concept C (low carbon - medium carbon equivalent, plate thickness 17mm)

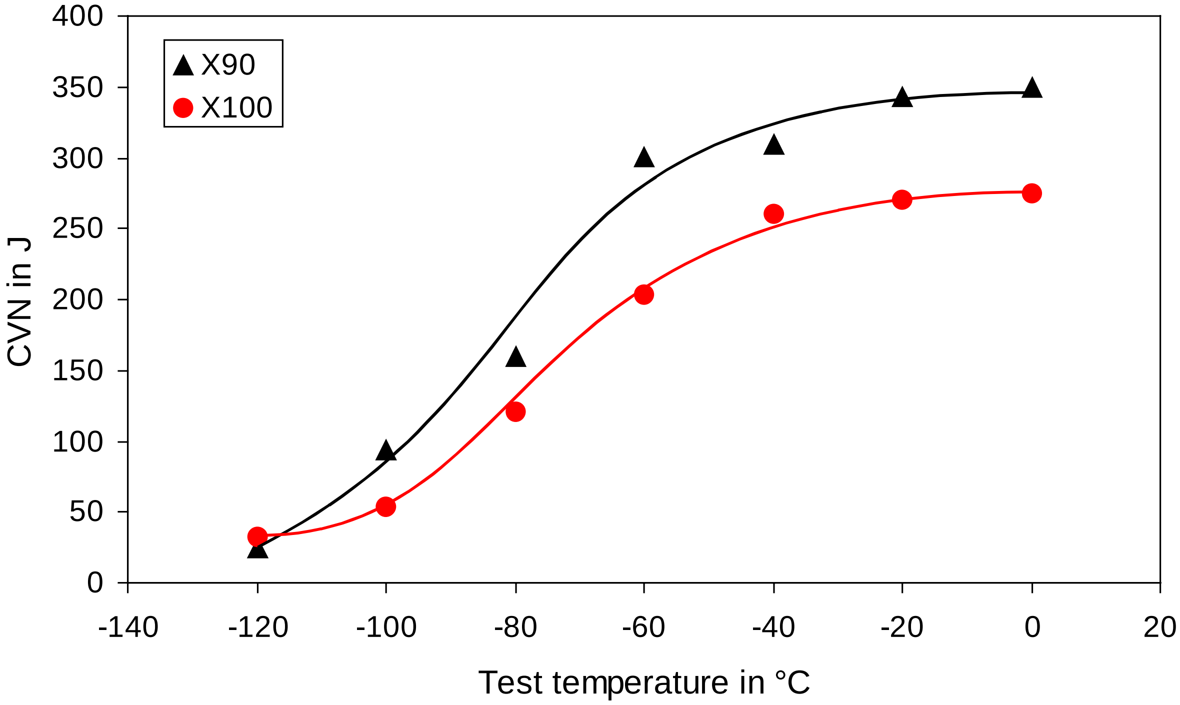


Figure 13: CVN impact transition curves in transverse direction for grade X90 and X100 for steel concept C (low carbon - medium carbon equivalent, plate thickness 17mm)

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