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New Developments on Arctic Steels by Application of TMCP Technology

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ABSTRACT

Explorations of new oil and gas fields in harsh arctic surroundings and the possibility of passing through the Northeast Passage lead to new challenging requirements for offshore constructions. Further developments of steel grades are of basic importance to meet the increasing demand on plates for structural applications.

The challenging new requirements for existing steel grades are an improved toughness at lower temperatures without decrease of strength and an adapted weldability.

Therefore, advanced base material properties of heavy plates as well as HAZ (Heat Affected Zone) behaviour have been developed by optimizing of the chemical composition and utilization of TMCP (Thermomechanical Controlled Process) technology.

In this paper, the development of high-strength heavy plates with improved low temperature toughness is described and illustrated with a recent application. Plates of grade S420G1/2 up to 65 mm thickness and Charpy impact properties down to -80 °C and CTOD (Crack Tip Opening Displacement)-properties down to -50 °C were successfully produced and delivered for the construction of an offshore loading tower in Siberia.

KEY WORDS: Offshore; steel development; arctic; low temperature; CTOD.

INTRODUCTION

During the last years, the demands on constructions and therefore on steel plates have been increased. Because of the low actual oil-price the investigations in the arctic region were reduced (Reuter, 2015; Meinert, 2015). However, there is still a rising potential for more export terminals in Arctic areas due infrastructure constraints over land because of the possibility of passing through the Northeast Passage. Thus more offshore constructions like terminals and platforms can be expected for the future (Fig. 1). Lower ambient and service temperatures have to be considered. Lowest Anticipated Service Temperature (LAST) in the North Sea is -10 °C, whereas structures in the arctic region should anticipate for a service temperature between -50 and -60 °C. In order to ensure safe service in winter periods, sufficient fracture toughness shall be proven for highest thickness involved at the anticipated LAST.

Weldability testing of the applied materials is used to ensure sufficient fracture toughness after fabrication welding. GCHAZ (Grain Coarsened Heat Affected Zone) and IC/SCHAZ (Intercritical/Subcritical Heat Affected Zone) are verified for fracture toughness while welded with

Figure 1. Loading tower and ship in Siberia (Bluewater, 2015).

the ultimate lowest and highest heat input anticipated during fabrication welding. Arctic application represents the severest challenge for structural steel plates. In order to improve the workability and weldability one aim of the design of the production of steel plates is to reduce the carbon equivalent.

A precise understanding of the metallurgical mechanisms and parameters controlling the microstructural evolution during processing provides the basis for a customized and optimized design. The most important elements of the metallurgical approach are low carbon chemistry, a well balanced alloying, good reproducibility of a high level of steel cleanliness and homogeneity.

The availability of high quality slabs and the use of TMCP technology (DeArdo, 2009; Schütz, 2001; Schwinn, 2011) makes tailor-made solutions for demanding applications possible.

PRODUCTION ROUTES

Dillinger Hütte is an integrated plant and optimizes the whole production line from slab to plate production with cokery, blast furnace, steel making plant, casting line and rolling mill. Thus, there is a production line with quality from a single source. Particularly, the production of heavy plates with low temperature toughness requires the use of clean slabs which is reached by a secondary metallurgy with 100 % vacuum degassing. The steel plant is able to produce the world's thickest slab with thickness of 500 mm (Naumann, 2015). Therefore regarding good properties in the mid-thickness of the plates a high deformation ratio during rolling is available. Steel for low temperature service has very low carbon content lower than 0.06 % and an addition of microalloying elements (i.e. Nb, Ti) and solid-solution elements (i.e. Cu, Ni). The plates were produced with the TMCP-process (Fig. 2).

All process steps like slab reheating between 1000 and 1200 °C, deformation rate during two or three rolling stages at well defined temperatures, final cooling temperature between 300 and 600 °C and cooling rate lower 10 K/s were optimized to reach a homogeneous and extremely fine-grained microstructure.

New product developments are pushed forward by the R&D department, where basic investigations and process simulations are conducted. As a thorough microstructural characterization down to nanoscale is an integral part of the development process, scanning electron microscopy and EBSD (electron backscattering diffraction) are available and intensively used for analysis.

In order to develop welding properties, the Welding Laboratory of R&D is involved. Weldability is controlled by Gleeble simulation and full scale welding trials. In addition, qualification is carried out in-house.

PRODUCTION OF S420G1/2 WITH IMPACT TEST AT -40 TO -55 °C FOR THE NORTH SEA

The requirements on yield and tensile strength, Ch-V (Charpy V-notch) and CTOD-tests (Crack Tip Opening Displacement) of grade S420G1/2 as per European Standard EN 10225 and NORSOK Standard M-120 (Material data sheets for structural steels) are shown in table 1.

Table 1. Specified yield and tensile strength, Ch-V (base material and HAZ) and CTOD-tests (HAZ) of grade S420G1/2 as per EN 10225 and NORSOK (thickness 65 mm).

Spec.	CE, %, max	Grade	YS, MPa	TS, MPa
EN10225	0.42	S420G1/2	380	480-640
NORSOK	0.42	S420G1/2	420-540	500-660

Spec.	ChV, °C	ChV, J(av)	CTOD,°C	CTOD, mm
EN10225	-40	60	-10	n.d.
NORSOK	-40	60	-10	0.25

Fig. 3 shows results of production of plates with thickness of 65 mm for the North Sea (Ch-V at -40 °C) that can be produced with a carbon equivalent of max 0.38 %. The carbon content is less then 0.05 %. Solid-solution elements are Copper, Nickel, Molybdenum and/or Chromium (Cu+Ni+Mo+Cr <= 0.90 %) that can be used to increase tensile properties and to suppress early ferrite formation. With an optimized TM-process including accelerated cooling, this chemical composition is used to achieve toughness properties down to -60 °C at mid-thickness on plates.

But it is also evident that for the given plate thickness individual values start to scatter specified Ch-V-results at -70 °C or lower can only reached with a risk of 10 %. This leads to new developments of arctic steel grades.

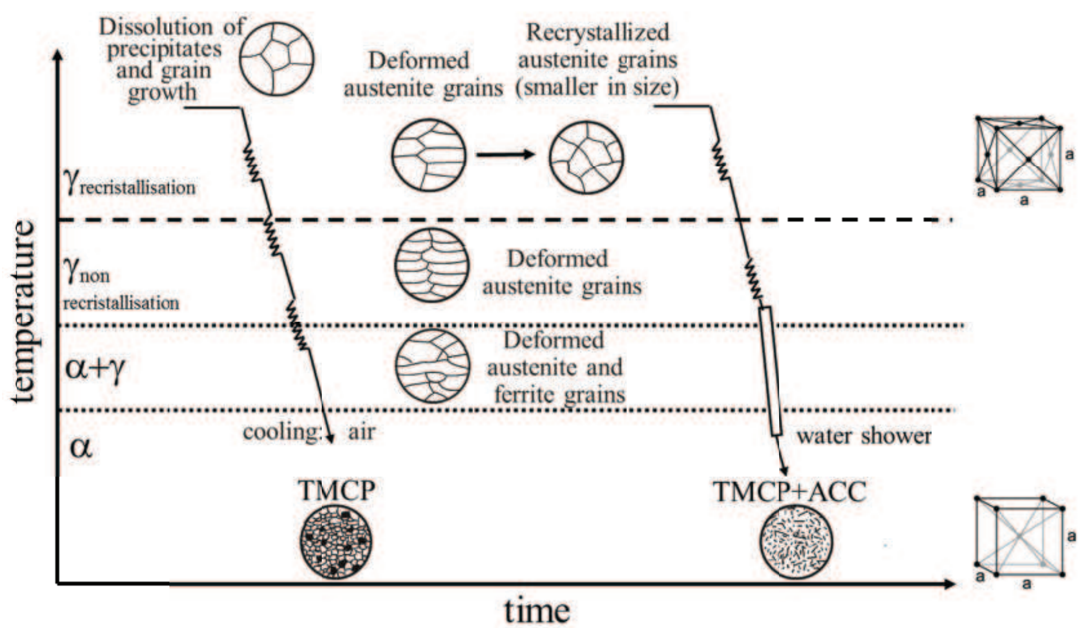

Figure 2. Process design types of Themomechnical Controlled Process (TMCP).

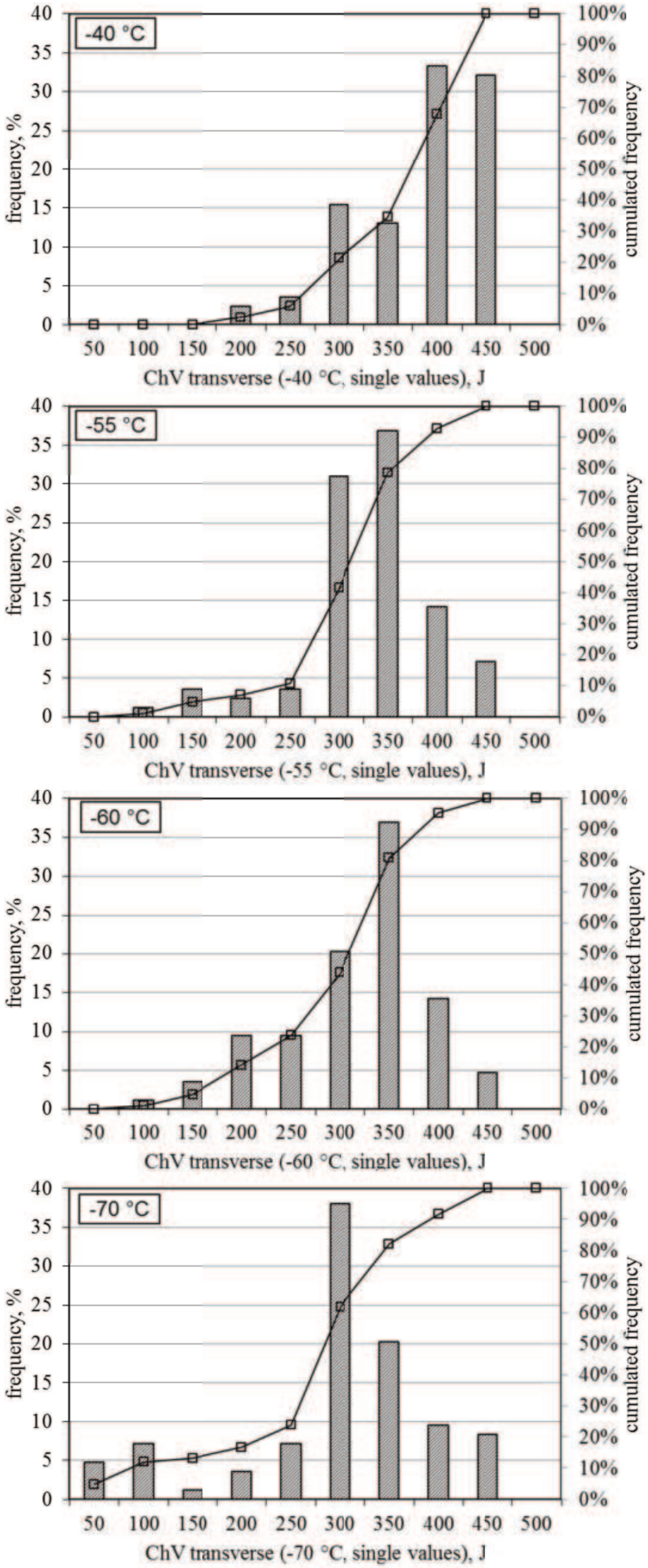

Figure 3. Results of Ch-V-tests in mid-thickness position of plates of grade S420G1/2 for North Sea applications.

WHAT MEANS ARCTIC OFFSHORE STEELS?

Although there is no common definition for arctic regions and their requirement profiles, one can say that arctic regions have rough climate, seasonal or permanent frost and ice and ambient temperatures typically lower than -30 °C. Arctic materials should be defined by LAST related requirements. The test temperature of CTOD-test should be equal LAST and of ChV-tests LAST -30 °C. If LAST is -50 °C in the arctic region the test temperature of CTOD-tests is -50 °C and of ChV-tests -80 °C (Fig. 4).

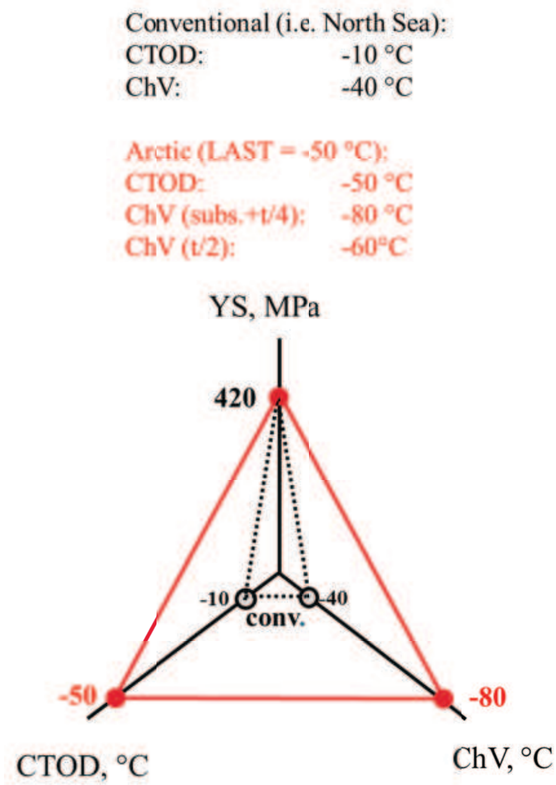

Figure 4. Example of demands on arctic steels.

DEVELOPMENT OF S420G1/2 WITH IMPACT TEST AT -80 °C AND CTOD-TEST AT -50 °C FOR ARCTIC REGIONS UP TO 65 MM PLATE THICKNESS

Steel plates with high strength and improved low temperature toughness can be obtained by an optimized microstructure with regard to grain size, morphology and phase distribution. The desired combination of mechanical properties is realized by a precise control and a targeted adjustment of steel composition, reheating, rolling, cooling and tempering process.

Plates in the thickness range from 10 to 65 mm were recently produced for an arctic offshore project. Within this project an arctic loading tower was constructed to bunker oil on ships in Siberia. The tower was designed and built by Bluewater Energy Services B.V. In close cooperation with Bluewater Dillinger Hütte developed this new steel design and delivered all the plates for this project (Fig. 5)

Figure 5. Arctic loading tower in Siberia (Bluewater, 2015). Results of plates with thickness of 65 mm are presented in Figs. 6 and 7.

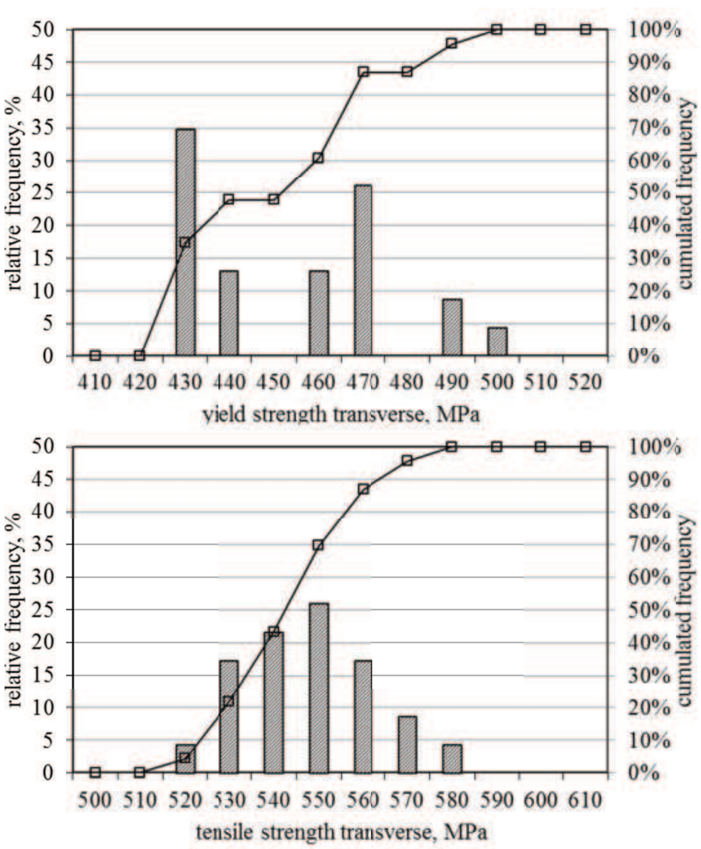

Figure 6. Results of tensile tests of production of arctic steel plates with thicknesss of 65 mm.

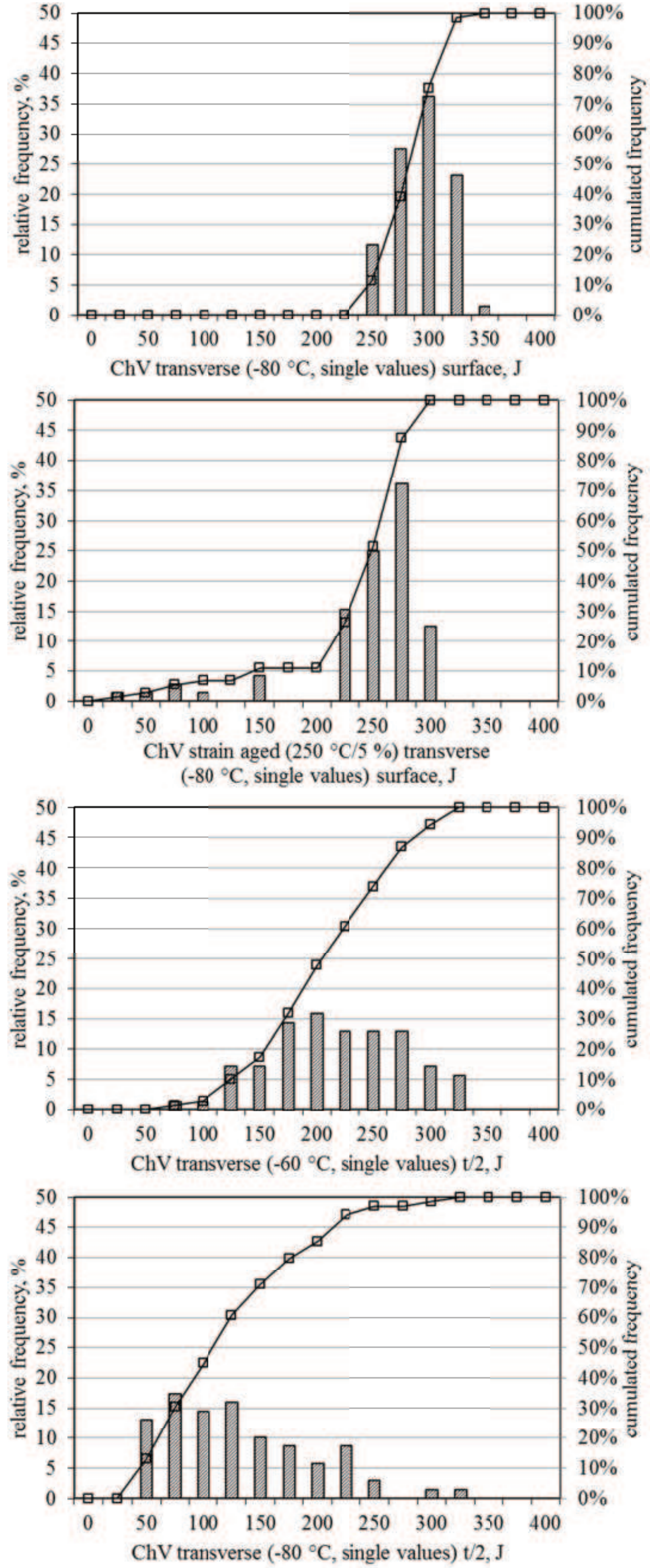

Figure 7. Results of Ch-V-test tests of production of arctic steel plates with thickness of 65 mm.

Up to a thickness of 65 mm a grade S420G1/2 also with NORSOK-Specification (Table 1) can be produced. Results of Ch-V-tests on surface at -80 °C in mid-thickness at -60 and -80 °C and in strain aged condition in -80 °C show very consistent and reliable level of impact toughness levels (Fig. 6 and 7).

The qualification for this project encompasses also intensive weldability tests to prove that also the HAZ zone has sufficient toughness and resistances against brittle fracture at low temperatures.
Two heat inputs (0.8 kJ/mm and 3.5 kJ/mm) as required within EN 10225, option 18, have been carried out for each chemical composition. Table 2 and 3 show the impact toughness of the HAZ for different notch locations (i.e. fusion line, fl+2 mm, fl+5 mm) tested at -80°C for the highest thickness range (> 25 mm) .
The average values are higher than 100 J, thus exceeding the base material requirements by far.

The resistance against brittle fracture was tested on full thickness CTOD specimens at -50 °C for notch position CG-HAZ and IC/SC HAZ. Table 4 shows that all the values are in line with the acceptance criteria from Offshore Standard DNV-OS-C401 (Ch.2 Sec.1).

Table 2. Results of impact tests of welded joints with heat input of 0.8 kJ/mm at -80 °C.

subsurface (cap)	single values, J			average, J
fusion line	280	220	109	203
fusion line+ 2 mm	231	218	232	227
fusion line + 5 mm	271	248	246	255
mid thickness	single values, J			average, J
fusion line	157	84	117	119
fusion line+ 2 mm	211	216	223	217
fusion line + 5 mm	222	225	216	221
lower subsurface	single values, J			average, J
fusion line	232	114	258	201
fusion line+ 2 mm	219	211	229	220
fusion line + 5 mm	255	238	252	248

Table 3. Results of impact tests of welded joints with heat input of 3.5 kJ/mm at -80 °C.

subsurface (cap)	single values, J			average, J
fusion line	159	167	97	141
fusion line+ 2 mm	292	269	240	267
fusion line + 5 mm	234	290	228	251
mid thickness	single values, J			average, J
fusion line	195	183	90	156
fusion line+ 2 mm	262	235	274	257
fusion line + 5 mm	183	98	201	161
lower subsurface	single values, J			average, J
fusion line	219	199	210	209
fusion line+ 2 mm	295	269	296	287
fusion line + 5 mm	231	234	298	254

Table 4. Results of CTOD tests of welded joints at -50 °C.

	heat input, kJ/mm	CTOD, mm, single values				
GCHAZ	0.8	1.70	0.31	1.71	0.63	1.74
IC/SCHAZ	0.8	0.86	1.64	1.28		
GCHAZ	3.5	0.87	1.65	0.31	0.44	1.25
IC/SCHAZ	3.5	0.28	0.15	0.86	1,67	

VARIATION OF MICROSTRUCTURE AND PROPERTIES BY ACCELERATED COOLING

For the thickness of 65 mm different cooling parameters indcluding cooling speed were tested to optimize the properties for strength and impact test. With MULPIC (Multipurpose Interrupted Cooling) cooling device it is possible to reach various final cooling temperatures or cooling rates. Therefore it is possible to realize different cooling concepts (Fig. 8).

Impact properties were tested on surface position (including strain aged tests condition to simulate the forming and aging) and in mid-thickness (Fig. 9).

It is obvious that with the process of higher cooling rate the yield strength (and also the tensile strength) is higher in comparison with lower cooling rate. On the other hand, the Ch-V-toughness is slightly detoriated at higher cooling rates.

The effect of the different cooling designs on microstructural evolution is illustrated in Figs. 10 and 11. Changing the cooling conditions refines the microstructure and the bainitic ferrite matrix becomes more irregular in shape. Furthermore, the small islands formed by the second phase disappear almost completely for the process with the higher cooling rate. However, the toughness-properties in mid-thickness at -80 °C are scattering and need further development.

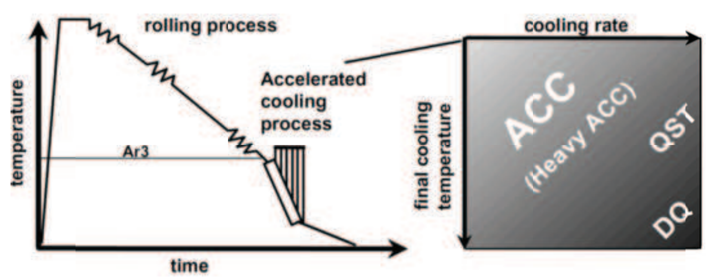

Figure 8. Illustration of TMCP and variants of accelerated cooling (Schütz, 2001): ACC (Accelerated Cooling), QST (Quench and Self-Tempering) and DQ (Direct Quenching).

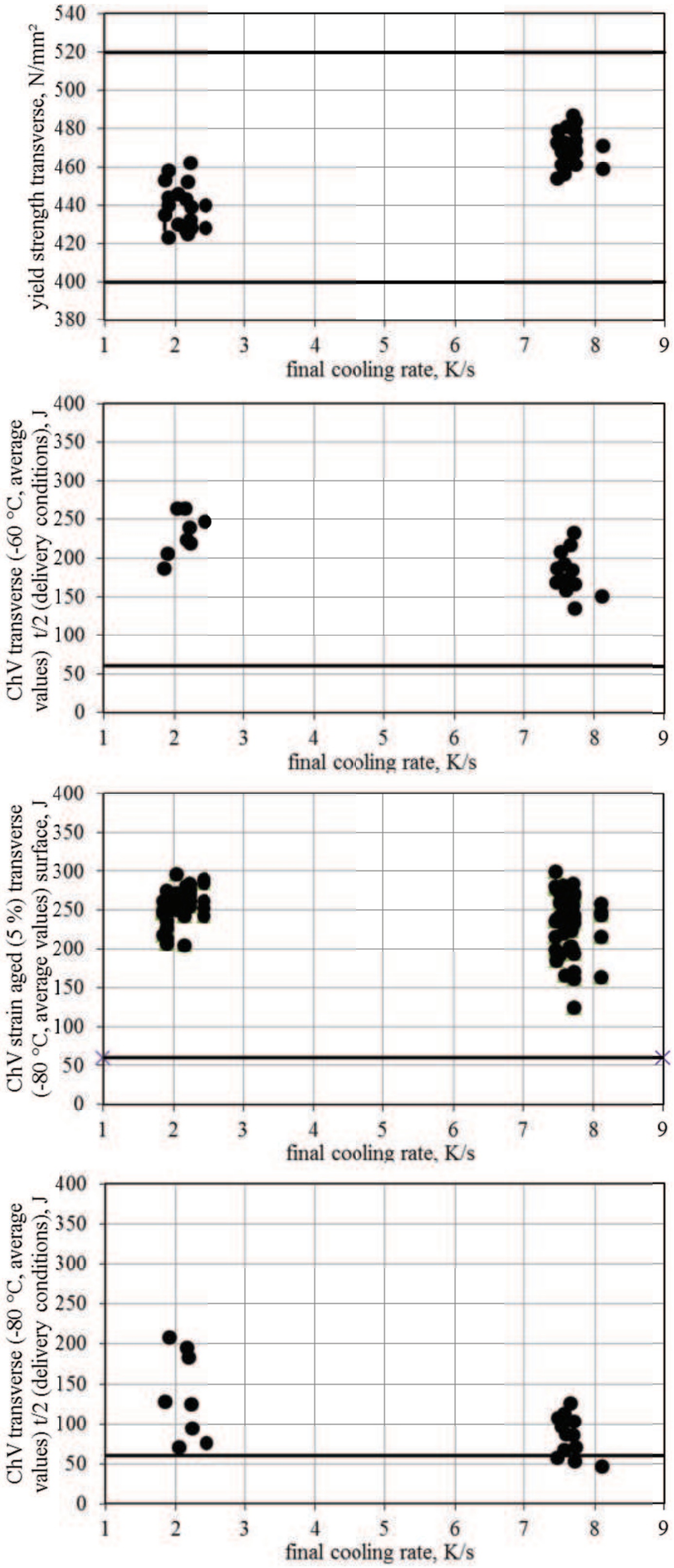

Figure 9. Results of tensile and Ch-V-tests (also in strain aged condition with different aging conditions) of production of arctic steel plates with different cooling design. (low: ACC, high: Heavy ACC)

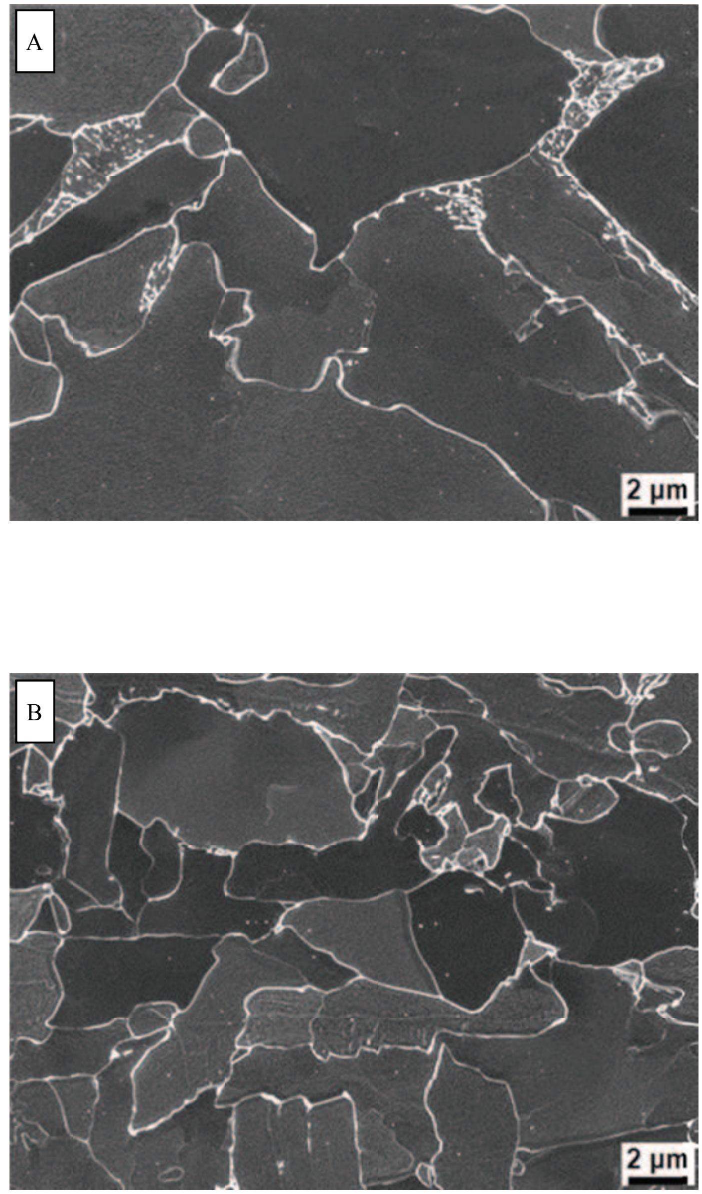

Figure 10. Microstructure of arctic steel plates with different cooling design. (A) lower and (B) higher cooling rate and final cooling temperature.

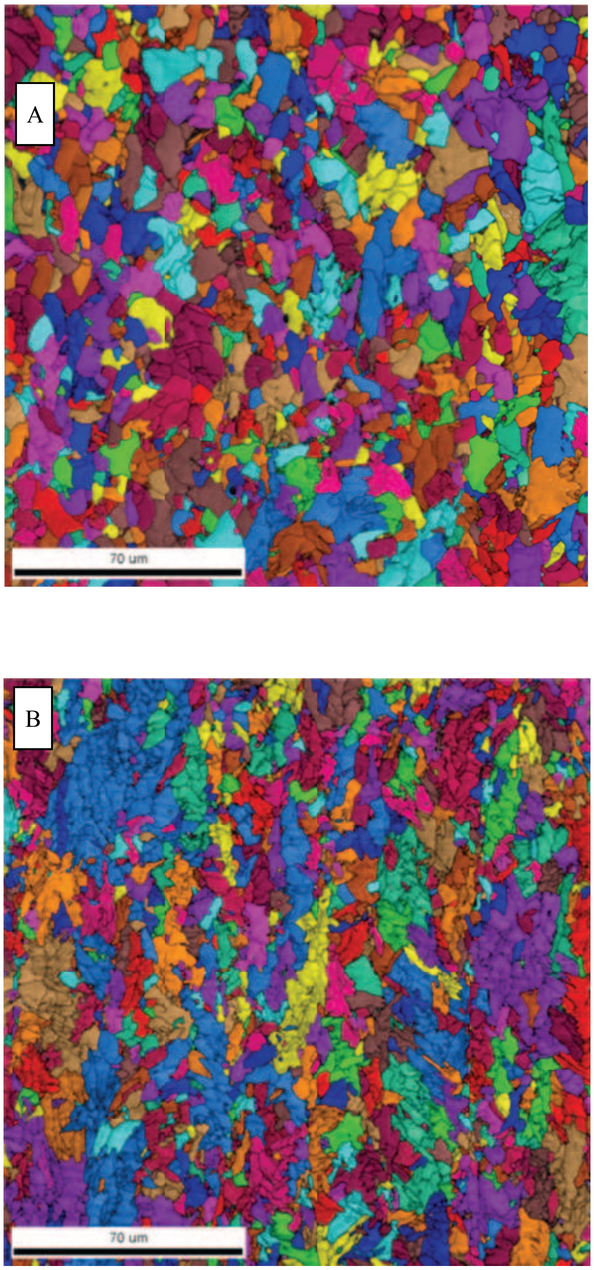

Figure 11. EBSD scans of the different cooling designs showing crystal orientation (inverse pole figure coloured map). (A) lower and (B) higher cooling rate and final cooling temperature.

OPTIMIZATION OF STEEL DESIGN BY VARIATION OF COMPOSITION

To improve the mid-thickness properties at -80 °C without decreasing the yield strength and the toughness in strain aged condition a new composition with a lower carbon equivalent was developed. With this composition the grade S420G1/2 per EN10225 can be reached.

Fig. 12 shows the transition curve of Ch-V-tests in as delivered and in strain aged condition.

At -80 °C the toughness level of 60 J and more can be reached. Also in the strain aged condition the level is sufficient.

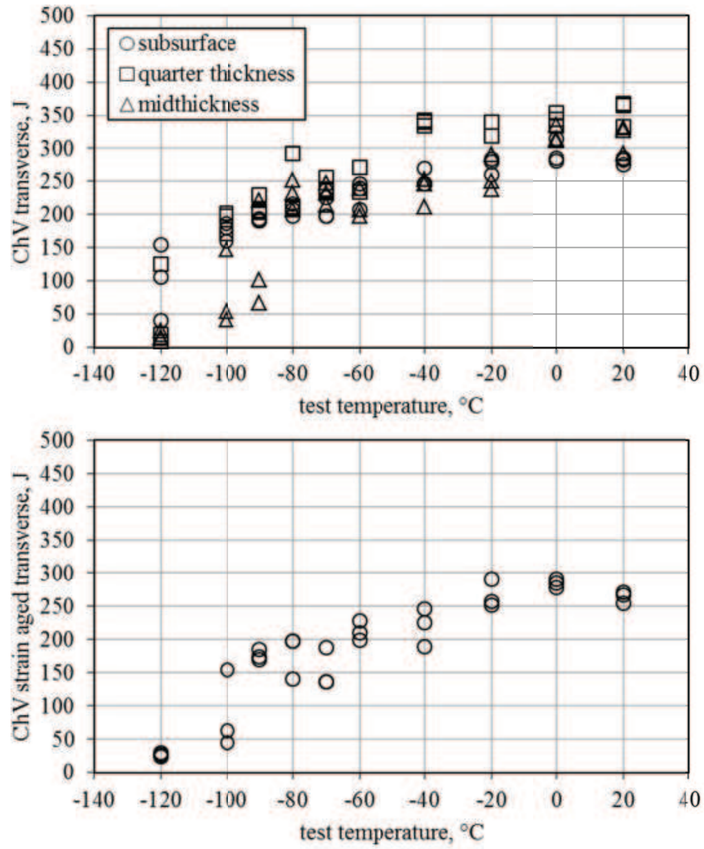

Figure 12. Transition curves of Ch-V-tests and strain aged Ch-V-tests with optimized composition.

CONCLUSIONS

New demands for arctic offshore structures with design temperatures lower than -30 °C pushed the development of new structural steels forward. Dillinger Hütte has developed and already produced large tonnages of these steel plates with grade S420G1/2 up to 65 mm thickness and excellent charpy impact porperties at low temperatures down to -80 °C and CTOD-properties down to -50 °C.

As a result it is possible to prospect and explore arctic regions by application of steel.

REFERENCES

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DeArdo, AJ, Hua, MJ, Cho, KG, Garcia, CI, (2009). "On strength of microalloyed steels: an interpretive review," *Materials Science and Technology,* Vol. 25, No. 9, 1074-1082.

Meinert, P, (2015). http://www.sz-online.de/nachrichten/shell-gibt-bohrungen-in-der-arktis-auf-3211046.html.

Naumann, P, (2015). "Weltklasseformate", *Us Hütt* 3 (2015), 12.

Reuter, B, (2015). "Schneewittchen kommt zu spät," *WirtschaftsWoche*, 8, 62-65.

Schütz, W, Kirsch, J, Flüss, P, Schwinn, V (2001). "Extended property combinations in thermomechanically control processed steel plates by application of advanced rolling and cooling technolog,y" *Ironmaking and Steelmaking*, Vol. 28, No.2, 180-184.

Schwinn, V, Bauer, J, Flüss, P, and Amoris, E (2011). "Advanced TMCP steel plates for pipelines and Structurals," *Materials Science Forum Vols*. 706-709, 2812-2817.