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Recent developments and applications of TMCP steel plates★

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Key words:
TMCP; plate; development; application; metallurgical design; microstructure

Abstract – The developments of plates are strongly driven by demands from high-sophisticated pipeline and structural applications. Such needs reflect in plates with higher thickness, larger width, higher toughness also at lower temperatures, higher strength and/or better resistance to sour environments. The requirement profiles are, in some cases, exceptional and have become achievable, in an extreme combination of alloying and processing technologies, only as a result of comprehensive development work and plant investments. A broad potential for innovation derives by the utilization of the key-technology TMCP (Thermo-Mechanical Controlled Process). The status of present-day heavy plate production will be presented. An outline of the production facilities, routes and process variants will be given. As a central element to achieve high-class requirements, aspects and parameters of the metallurgical design will be explained. The utilization will be explained and illustrated with selected recent applications.

Mots-clés :
TMCP ; tôles ; développement ; application ; process de fabrication ; microstructure

Résumé – Développements récents et application aux aciers thermomécaniques pour pipelines et structures métalliques sophistiquées. Le développement des tôles est fortement conditionné par la demande de pipelines et de structures métalliques présentant des exigences toujours plus élevées. Ceci se traduit par un besoin de tôles de plus forte épaisseur, de plus grande largeur, avec des propriétés de résilience plus élevées à plus basse température, de résistance à la traction plus élevées et/ou avec un meilleur comportement en milieu acide. Le respect de l'ensemble de ces exigences est, dans certains cas, possible grâce à l'utilisation d'acier présentant une combinaison particulière d'éléments d'alliage et à l'application de procédés de transformation spécifique en tôlerie ; ceux-ci sont le résultat d'un travail d'investigation et d'investissements dans les outils. L'utilisation des traitements thermomécaniques (TMCP) constitue, pour une grande part, le point clé de ces innovations. La situation actuelle de la production des tôles fortes est présentée. Une description des possibilités de production et des différentes routes métallurgiques est faite. L'effet des paramètres de process de fabrication sur les propriétés métallurgiques permettant d'atteindre de tels niveaux d'exigences est expliqué. Des exemples de réalisations récentes sont présentés.

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There is general consensus about a strong growth in the overall gas demand on a medium-long term time scale. As shown in Figure 1, EIA predicts an increase of the total world energy consumption from 406 quadrillion BTU in 2000 to 739 quadrillion BTU in 2035 [1]. It includes an increase of natural gas consumption from 91 quadrillion BTU in 2000 to 162 quadrillion BTU in 2035.

There is also a mainstream trend to increase the amount of alternative energy supplies. The amount of offshore wind farms was already and will be raised considerably in the near future. It is outlined in Figure 2 that the net electricity generating installations in the EU largely increased from 2000 to 2009 for the natural gas and wind energy,

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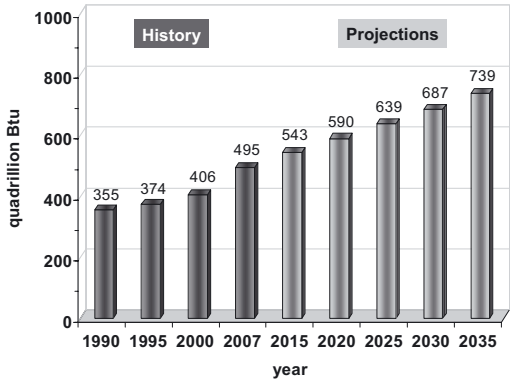


Fig. 1. Total world consumption of marketed energy from 1990–2035 [1].

Fig. 1. Consommation mondiale totale d'énergie de 1990 à 2035.

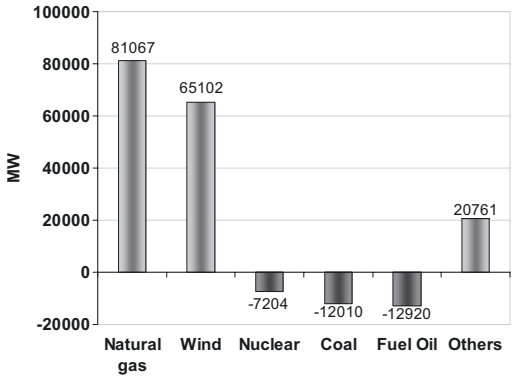


Fig. 2. Net electricity generating installations in EU from 2000–2009 [2].

Fig. 2. Évolution entre 2000 et 2009 de la puissance électrique produite à partir du gaz naturel/éolien/nucléaire/charbon/pétrole/autres.

while it decreased for nuclear, coal and fuel oil [2].

The European Commission stated that Europe's future economic growth and stability depend on timely and adequate investments in the energy infrastructure [3]. In 2006, 84% of natural gas supply to the EU came from just three countries [4]: 42% from Russia, 24% from Norway and 18% from Algeria. As a consequence a number of pipeline projects were put on track or are envisaged to bring gas from energy-rich Russia, better interconnect all EU member states, reduce the isolation of the more remote nations and diversify gas imports for a greater security of gas supplies.

To realize all these objectives both technically feasible and economically viable advanced plates are a fundamental prerequisite. The paper compiles the technological status, key elements to achieve the objectives and recent accomplishments of such plates.

1 Production of heavy plates

1.1 Steelmaking

The first step of production of heavy plates with high quality requirements is the steelmaking process. Usually the BOF-route on the basis of hot metal is used. The principal steps are hot metal desulphurization, BOF process, secondary metallurgy and continuous casting. The objectives of the steelmaking process are the adjustment of low contents of sulphur, hydrogen, nitrogen, total oxygen and in some cases also phosphorus [5, 6]. The slabs have to be free of inner and outer defects that mean a minimum of center segregation and surface defects. Highest amount of steel cleanliness can be achieved with a vertical caster. To minimize center segregation soft reduction has to be installed in the area of the crater end [7]. For the benefit of thick plates the maximum slab thickness was recently extended to 450 mm.

1.2 Plate rolling

Aspects of technically challenging property requirement profiles, fabrication and manufacturing cost savings gained more and more importance and led to the development of the modern generation of micro-alloyed TMCP (Thermo-Mechanical Controlled Process) plates. TMCP can be described as a process which aims at achieving an internal structure including a fine effective grain size, permits a favorable combination of service properties, is tailored to the steel composition and is composed of a sequence of specific processing steps controlled in terms of thickness, time and temperature (Fig. 3). This entails suitable reheating of the slabs within well defined tolerances to achieve the desired austenite grain size and dissolution of micro-alloying elements. The proper final internal structure is achieved by rolling

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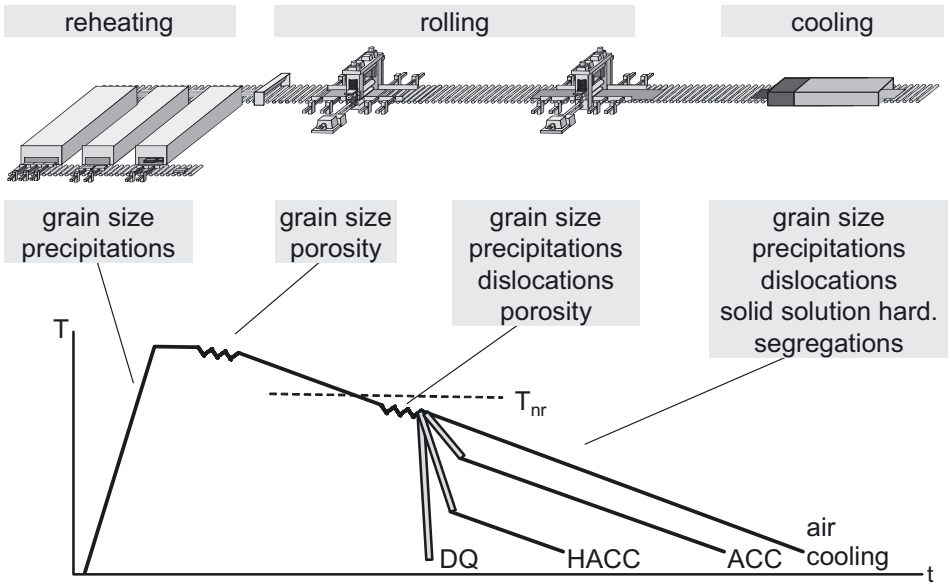


Fig. 3. Possibilities and influencing factors on properties during TMCP.
Fig. 3. Mécanismes et facteurs influents sur les propriétés durant le cycle thermomécanique.

on powerful rolling stands with specific deformations at different temperatures and accelerated cooling (ACC) after final rolling. Main cooling parameters influencing the microstructure to produce advanced steels are the CR (cooling rate) and FCT (finish cooling temperature). The balanced combination of CR and FCT in its variety of ACC, Heavy ACC (ACC with increased cooling rate), DQST (Direct quenching and self tempering) and DQ (Direct quenching to room temperature) opens the possibility to produce suitable microstructure components for all steel grades. That is why the MULPIC (Multi Purpose Interrupted Cooling) cooling device is installed in the plate mills of Dillinger Hütte GTS, which allows a wide range of heat flux density and a high flexibility in process design [8].

2 Metallurgical design and features

Metallurgical mechanisms which permit the achievement of the required mechanical and technological properties must be activated by alloying and at the different plate making stages. Tools and mechanisms to affect properties are shown in schematic and exemplary form in Figure 4 The proper microstructural design in terms of small effective grain sizes and second phase constituents has become a central element. This has to be seen as a consequence of the fact that the decrease of the grain size is the only measure to increase strength and toughness simultaneously. In this context bainitic transformation is now popularly referred and became an important component of advanced plates.

Figure 5 shows photographs of microstructures obtained by light microscopic investigations. It illustrates the influence of the type of cooling intensity in terms of air cooling, standard ACC with moderate cooling rate and Heavy ACC (HACC) with increased cooling rate. With the HACC-process a very fine and homogeneous bainitic microstructure is achieved.

For a proper description and understanding of bainitic microstructures advanced experimental techniques based on high resolution FEG-SEM (Field Emission Gun Scanning Electron Microscope) and EBSD (Electron Back Scattering Diffraction) are a prerequisite. For TMCP pipeline steels the variety and complexity of this structure is treated in more detail by Zajac et al. [9]. Clear differences in distributions of boundary misorientations and effective grain sizes were noted between upper, lower and granular bainites. Figure 6 compiles

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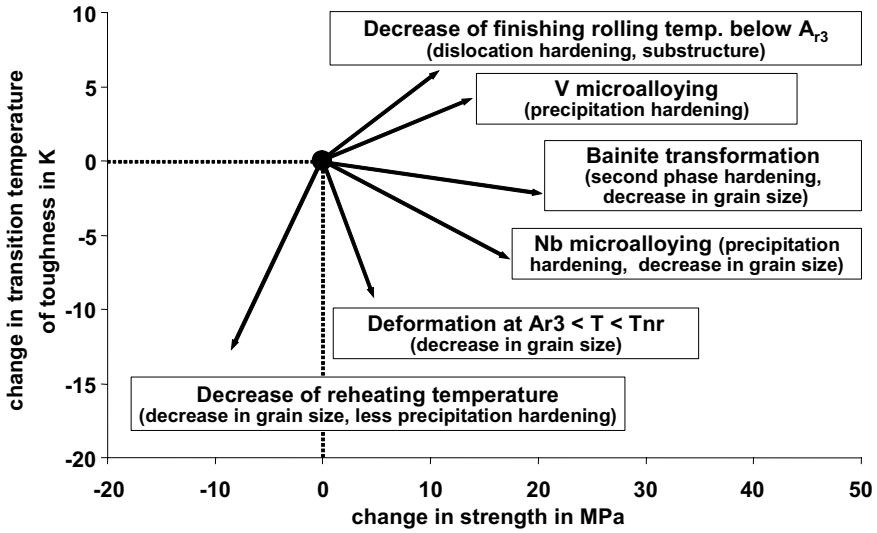


Fig. 4. Tools and mechanisms to affect metallurgical properties (exemplarily and schematically).
Fig. 4. Moyens et mécanismes associés influençant les propriétés métallurgiques.

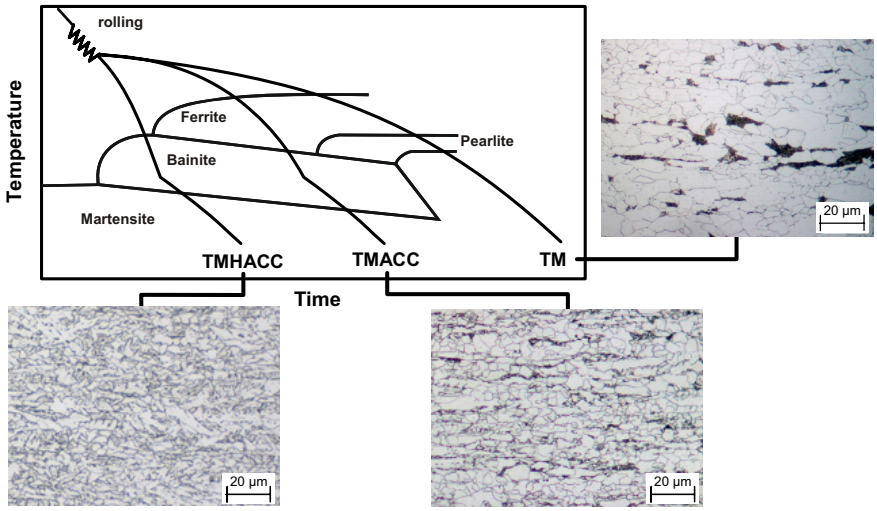


Fig. 5. Influence of the type of cooling after rolling on the microstructure (exemplarily).
Fig. 5. Influence des conditions de refroidissement après laminage sur la microstructure.

typical examples of appearances of these variants.

2.1 Aspects of steel design

The correlation of the tensile strength and Charpy-V-notch (CVN) impact energy at –40 °C with the finish cooling temperature and carbon equivalent (CE_{IIW}) is shown in Figures 7 and 8. In these figures the relative change of the tensile strength and CVN impact energy are presented:

$$\Delta TS = (TS - TS_0)/TS_0 \times 100 \quad (1)$$

with:

TS_0: reference tensile strength = lowest tensile strength at the highest finish cooling temperature for the investigated steel with the lowest CE_{IIW}.

TS: tensile strength for the specific steel type and selected finish cooling temperature.

$$\Delta CVN = (CVN - CVN_0)/CVN_0 \times 100 \quad (2)$$

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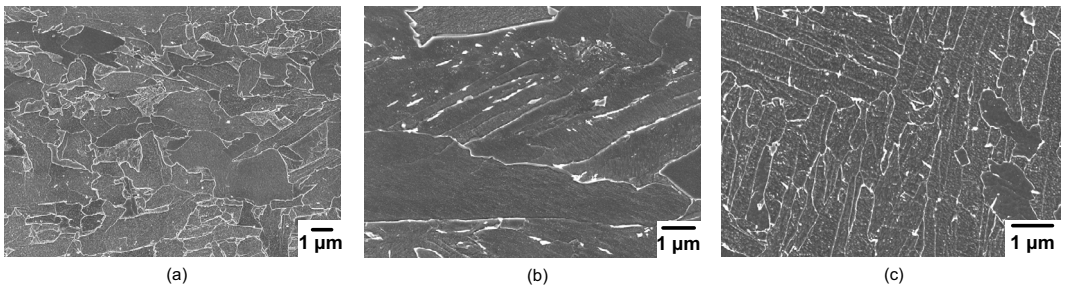


Fig. 6. Examples of bainite variants: (a) granular, (b) upper and (c) lower bainite.
Fig. 6. Differents type de bainite : (a) bainite granulaire, (b) bainite supérieure, (c) bainite inférieure.

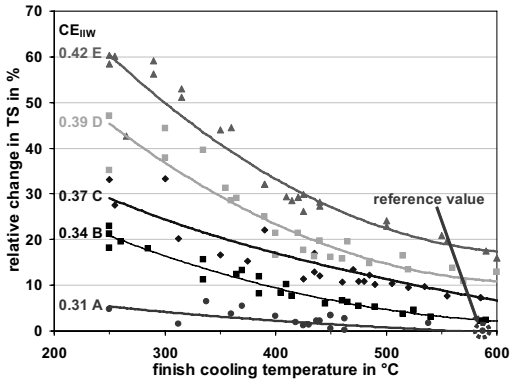


Fig. 7. Effect of finish cooling temperature and carbon equivalent on the relative change in tensile strength (NbV-steel, thickness 20 mm).
Fig. 7. Effet de la température de fin de refroidissement et du carbone équivalent sur la variation relative de la résistance à rupture (acier micro allié au NbV, épaisseur 20 mm).

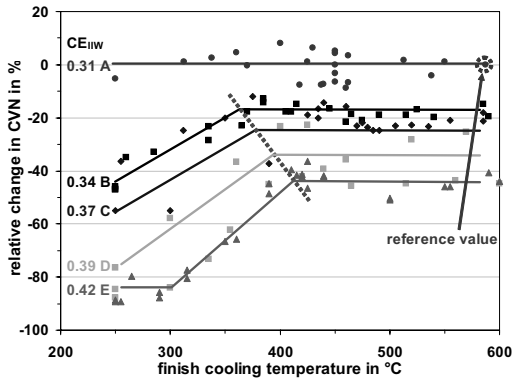


Fig. 8. Effect of finish cooling temperature and carbon equivalent on the relative change in CVN impact energyat –40 °C (NbV-steel, thickness 20 mm).
Fig. 8. Effet de la température de fin de refroidissement et du carbone équivalent sur la variation relative des propriétés de résilience à –40 °C (acier micro allié au NbV, épaisseur : 20 mm).

with:

CVN_0: reference CVN impact energy = highest energy at the highest finish cooling temperature for the investigated steel with the lowest CE_{IIW}.

CVN: CVN impact energy for the specific steel type and selected final cooling temperature.

The rise in strength for increasing carbon equivalent is higher for lower finish cooling temperatures on one side. On the other side, the lower the carbon equivalent the lower is the increase in strength with decreasing finish cooling temperatures. CVN impact energy shows also a similar correlation with the carbon equivalent and the finish cooling temperature. In addition sharp drops at defined finish cooling temperatures can be identified clearly. These drops correlate clearly with the appearance of a martensitic microstructure. This is demonstrated in Figure 9 for the steel with a CE_{IIW} of 0.42.

The properties can be also altered by the application of different cooling intensities. From Figure 10 it becomes evident that for the shown CuNiNb-steel with a carbon equivalent of 0.40 an efficient rise in strength from grade S420 to the next grade S460 can be obtained by the use of the HACC- instead of the standard ACC-process. The augmentation in strength by a decrease of the finish cooling temperature, even by 200 K, is obviously less than the increase by changing the process for the highest finish cooling temperature from ACC to HACC. It is further

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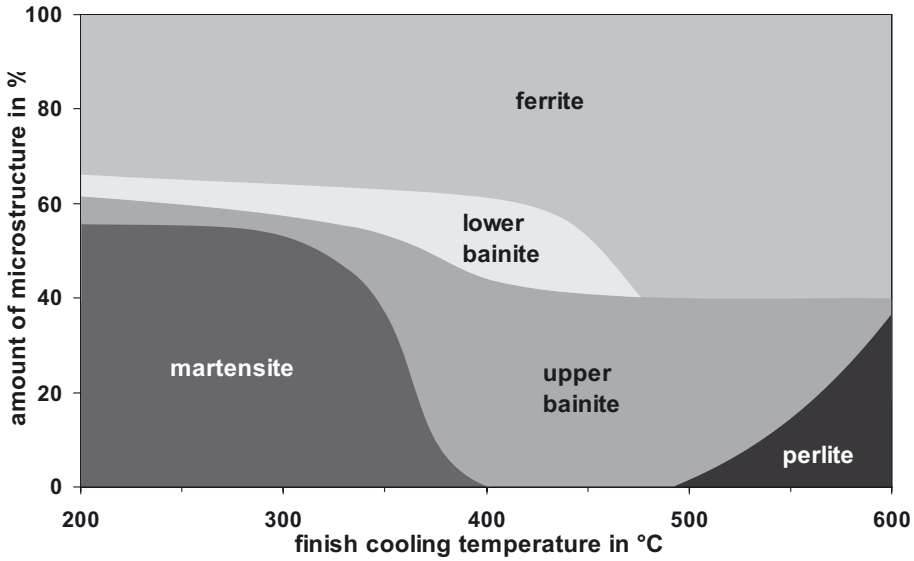


Fig. 9. Effect of finish cooling temperature on the amount of microstructures for steel *E* of Figures 7 and 8.

Fig. 9. Effet de la température de fin de refroidissement sur la proportion des constituants pour l'acier E des figures 7 et 8.

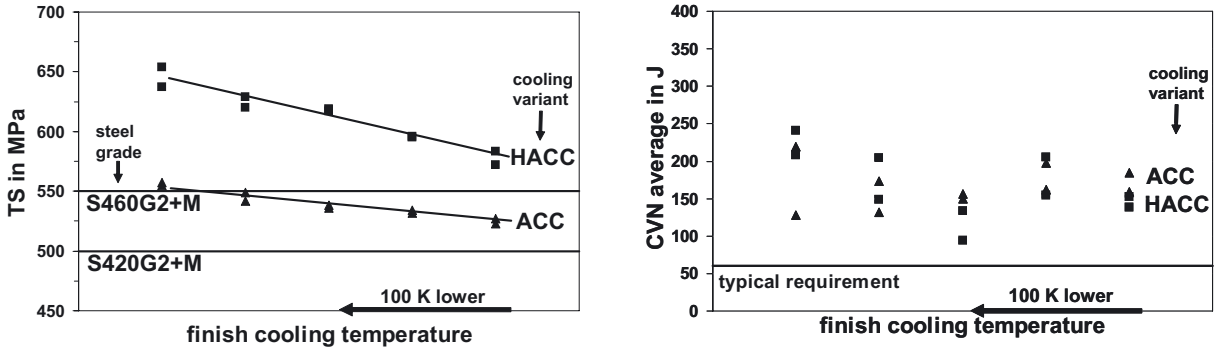


Fig. 10. Tensile strength and CVN impact energy at mid thickness position at –40 °C for ACC- and HACC- process for different finish cooling temperatures (CuNiNb-steel, CE_{IIW} ~ 0.40, thickness 50 mm).

Fig. 10. Évolution des propriétés de traction et de résilience à mi-épaisseur à –40 °C en fonction de la température de fin de refroidissement pour le process ACC et HACC (acier CuNiNb, CE_{IIW} ~ 0,40, épaisseur = 50 mm).

clearly demonstrated that for this steel the strength can be increased without harming the toughness at the shown testing temperature of –40 °C.

Figure 11 presents the toughness and tensile strength for different finish cooling conditions for a MoNiNbTi-steel with a CE_{IIW} of about 0.46. The best compromise of properties with TS above 800 MPa and CVN impact energies at –40 °C of more than 250 J are obtained by the application of the HACC-process with medium finish cooling temperatures. With higher cooling rates above 50 K/s, as achieved in the DQST- and DQ-process, tensile strength of around 900 MPa can be obtained together with CVN impact energies of still more than 100 J at –40 °C.

As pointed out above, the route to advanced plates goes via an intensified cooling process design in terms of reduced FCT and enhanced CR. This gives rise to new challenges for cooling device settings. Intensified cooling, especially combined with higher plate width or lower plate thickness, can lead to higher risk of flatness deviations due to bigger temperature gradients within the plates during the cooling process. The range of such flatness defect types is

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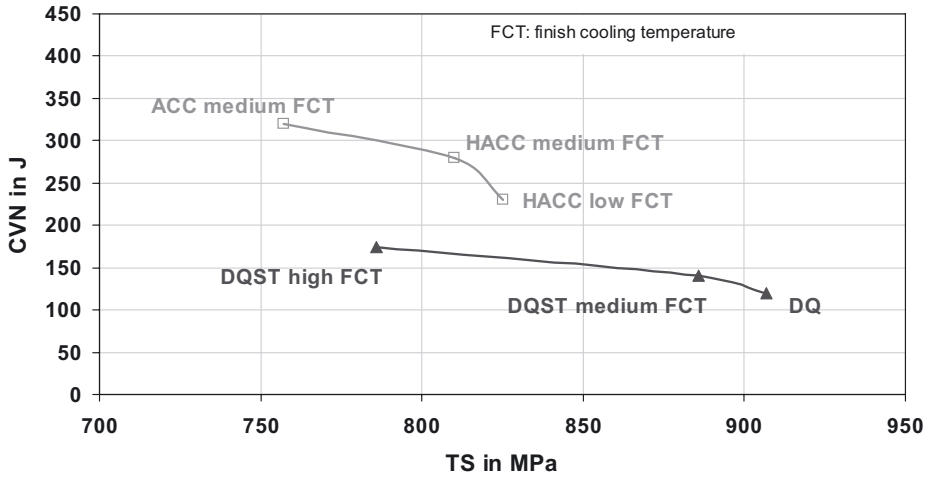


Fig. 11. Effect of finish cooling variant on CVN impact energy at –40 °C and tensile strength (MoNiNbTi-Steel, CE_{IIW} ~ 0.46, thickness 17 mm).

Fig. 11. Effet du mode de refroidissement sur les propriétés de résilience à –40 °C et de traction (acier au MoNiNbTi, CE_{IIW} ~ 0,46, épaisseur = 17 mm).

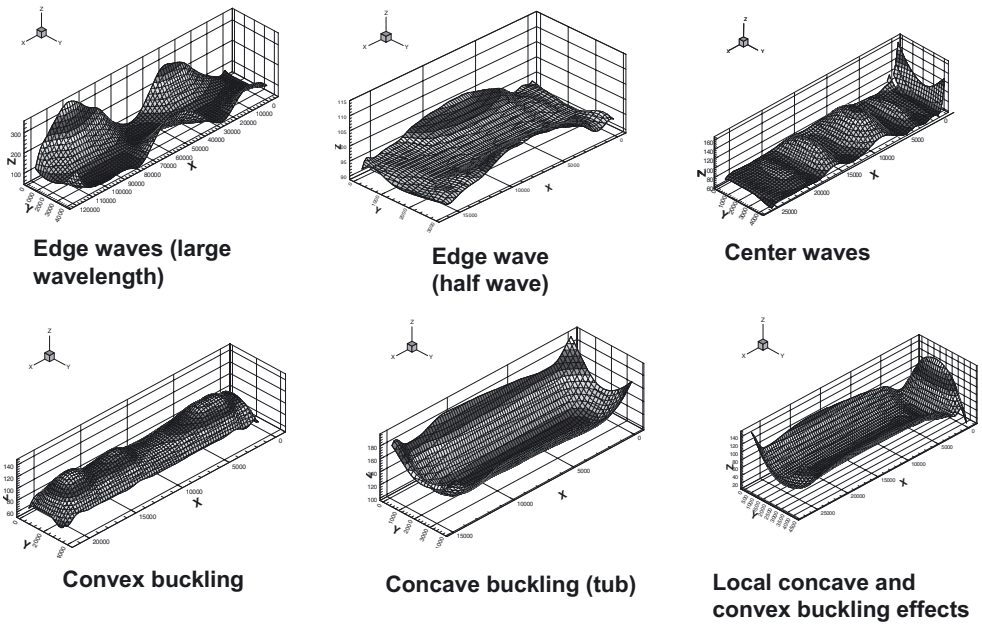


Fig. 12. Different types of flatness defects after cooling trials (evaluation of plate shape from on-line measurement).

Fig. 12. Type de défauts de planéité simulés lors d'essais de refroidissement (évaluation de la forme de la tôle par contrôle en ligne).

much broader than in case of rolling induced waviness. This is demonstrated in Figure 12 for some ACC-trial plates. The profiles were measured on-line with a laser based flatness measurement system directly after the cooling process.

Especially disadvantageous for the subsequent elimination by hot or cold levelling is the fact, that convex as well as concave flatness defect types can arise locally side by side on the plate. Therefore the plate producer has to maintain flatness during cooling process with an appropriate set

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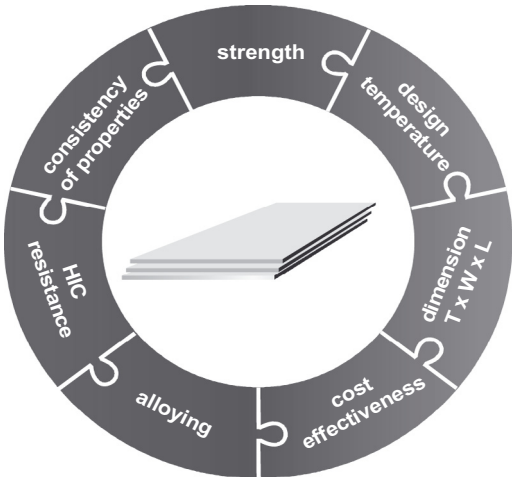


Fig. 13. Overall and linked requirement spectrum on plates.
Fig. 13. Définition des exigences sur tôles.

of cooling parameters in order to reduce the thermal gradients in longitudinal and transversal direction and residual stresses.

3 Current status of utilization and recent achievements

Figure 13 gives the components of a requirement profile. The requirements are in continuous evolution and are a key input factor for the plate design. As demonstrated above there is a close link between all these factors. Therefore it is a particular challenge to develop in different directions at the same time.

3.1 High strength application

An increase in strength is desired for a variety of reasons, e.g. to reduce weight or increase the pressure in a pipeline. As a consequence API-5L X80, L555MB or K65 is meanwhile widely established for onshore pipelines [10, 11]. Although grade API-5L X100 or even X120 were in the focus of large numbers of investigations, it is expected that steel grades will not be applied in the near future.

While the tensile test requirements are mainly based on the standard specification, the testing temperatures for CVN impact and BDWTT and the minimum requirement for CVN impact energy are a result of the specific application. Table 1 compiles exemplarily the requirements on pipe of plate deliveries for different projects with a minimum YS requirement of 555 MPa. The highest quality level is required for the K65. This steel is used for the Russian Bovanenkovo-Ukhta project with a pipe diameter of 56″ (1420 mm) which involves very broad plates of about 4500 mm.

The application of Grade S500M3z according to NORSOK standard in parts of a topside of an offshore platform resulted in a notable weight reduction in comparison with Grade S420M3z. A main cost benefit derived from the fact that such weight reduction enabled installation of the topside with a single lift operation [12].

3.2 Nord Stream pipeline

This offshore pipeline of grade SAWL-485 IFD in thicknesses from 26.8 mm up to 41 mm and a pipe diameter of 48″ (1153 mm) will have a total gas capacity of 55 bcm/a [13].

Two parallel pipelines with a length of 1224 km are currently in production from Portovaya Bay in Russia to the coast of Germany near Greifswald. For this pipeline huge quantities of advanced plates in all thicknesses were delivered by Dillinger Hütte GTS (at the end more than 1 million tons). Appropriate mill equipment, the application of a suitable quality assurance system and robust steel design are of particular importance in order to deliver such quantities with consistent properties.

Forming plates to pipes affects the properties. This has to be respected in the conceptual design phase of the plates. Figure 14 exemplifies relative frequencies for the Yield Strength and BDWTT achieved on plates with a thickness of 41 mm. All the properties were achieved in a narrow scatter band and the requirements after pipe forming were fulfilled reliably.

3.3 Low temperature application

The steel must possess specific requirements at a so called design temperature or at a lowest anticipated temperature. Depending on

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Table 1. Minimum requirements on the final pipe of plate deliveries for high strength applications with a minimum YS requirement of 555 MPa (examples).

Tableau 1. Exigences minimales sur la production de tôles pour des applications à haute résistance avec une exigence minimale YS de 555 MPa.

grade	Thickness in mm	TS in MPA	Elong. A5 in %	CVN		BDWTT	
				T in °C	*J*	*T* in °C	%SA
SAWL-555	33.8	625	18	–35	100	–	–
L555MB	14.5–22.8	625	18	0	150	0	85
K65	27.7	640	18	–40	200	–20	85

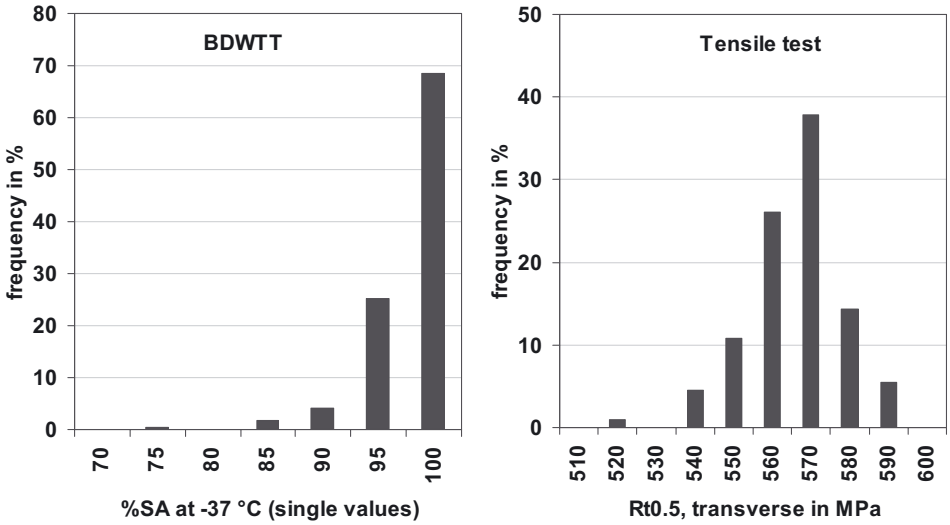


Fig. 14. BDWTT on specimens reduced to 19 mm thickness and YS (Rt0.5) from tensile test in transverse direction for grade SAWL-485 IFD with a thickness of 41 mm.

Fig. 14. Propriétés BDWTT sur éprouvettes rabotées à 19 mm et limite d'élasticité (Rt0,5) sens travers pour un acier de grade SAWL-485 IFD et d'épaisseur 41 mm.

the application this involves different kinds of testing at a given temperature: Charpy-V-Notch (CVN) impact, Batelle Drop Weight Tear (BDWT) and/or Crack Tip Opening Displacement (CTOD) tests. Because of more stringent safety criteria or application in very cold areas, testing temperatures down to –40 °C or even –60 °C are more and more demanded.

The compressor station of Portovaya will be a starting point for gas supplies via the Nord Stream gas pipeline [14]. It requires pipes of grade API-5L X70 up to a thickness of 39 mm and with requirements for arctic application. For this project the delivered plates were produced with a tailored process to achieve very fine grain. Figure 15 shows results for BDWTT at a very low temperature of –67 °C and yield strength for plates with a thickness of 39 mm. These results are remarkable.

An extraordinary challenge was the production of plates for a platform for the Sakhalin II project. As a result of the harsh environment a toughness of 60 J minimum has to be achieved at –60 °C at mid thickness position in combination with CTOD at –39 °C for the heat affected zone. TMCP-route with an adequate alloying concept was applied for thicknesses up to 90 mm. The CE_{IIW} of the steel used was about 0.43% [15].

3.4 Sour service

Hydrogen Induced Cracking (HIC) resistance is of vital importance in H_2S containing environments. To achieve such requirements consistently, the application of an integrated overall production concept plays a leading role [16].

For the different pipelines at the coast of Angola big quantities of plates were

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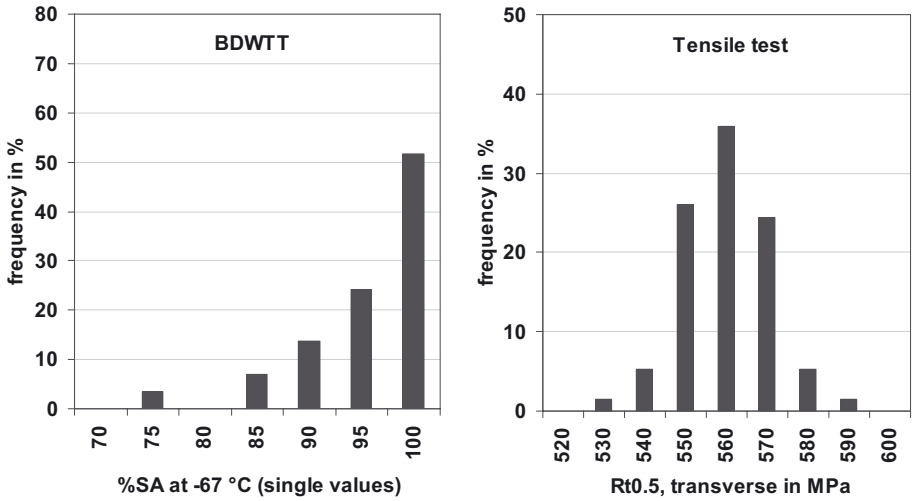


Fig. 15. BDWTT on specimens reduced to 19 mm thickness and YS (Rt0.5) from tensile test in transverse direction for grade API-5L X70 with a thickness of 39 mm.

Fig. 15. Propriétés BDWTT sur éprouvettes rabotées à 19 mm et limite d'élasticité (Rt0,5) en sens travers pour un acier de grade X70 selon API-5L et d'épaisseur 39 mm.

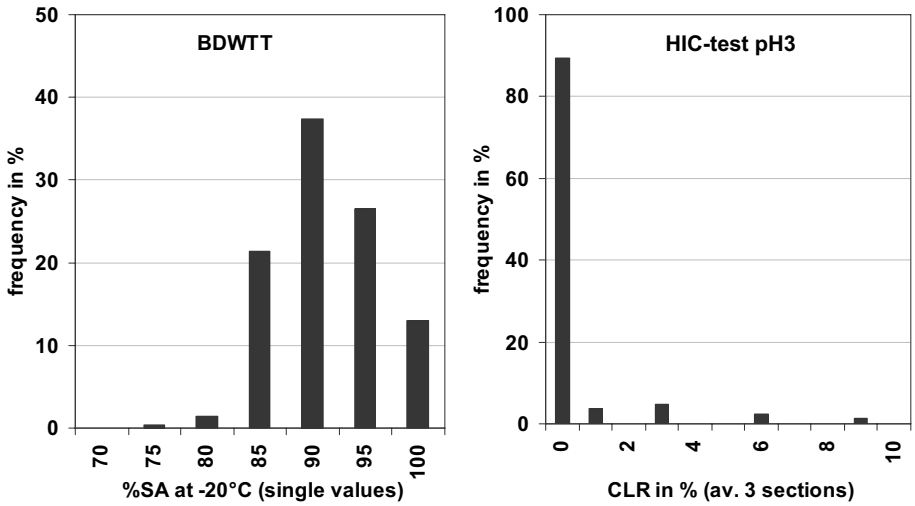


Fig. 16. BDWTT and HIC-test results on API-5L X65 plates with a thickness of 29.6 mm.

Fig. 16. Propriétés BDWTT et résultats HIC pour un acier de grade X65 selon API-5L et d'épaisseur 29,6 mm.

delivered. The specifications required grade API-5L X65 or similar with a thickness of up to 33.5 mm and with severe HIC-test requirements at pH 3. The forming of pipes resulted in total cold deformations of up to 7%. Cold deformation impairs the HIC resistance. The specific challenge was to deliver plates which meet the HIC-Test requirements even after pipe forming with such high cold deformations and to master the BDWTT requirements at –20 °C. Figure 16 graphs the results on BDWTT and HIC-test for the plates with a thickness of 29.6 mm. The requirements were clearly met on plate and on pipe as well.

As a result of elaborated development work and the application of the very latest technology on steel and plate making, Dillinger Hütte GTS is also prepared to meet the recent demand of grade API-5L X70 for sour service application. This is exemplarily demonstrated by Figure 17 where the BDWTT transition curve and HIC-test results achieved on plates with a thickness of

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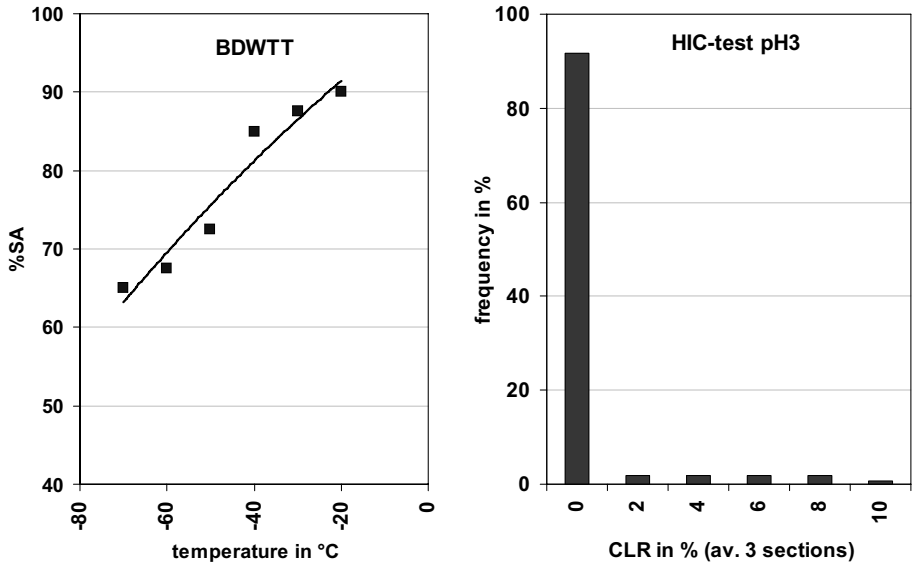


Fig. 17. BDWTT transition curve and HIC-test results on API-5L X70 plates with a thickness of 25.4 mm.

Fig. 17. Courbe de transition BDWTT et résultats d'essais HIC pour un acier de grade X70 selon API-5L et d'épaisseur 25,4 mm.

25.4 mm are presented. More than 90% of the specimens did not show any HIC.

3.5 Offshore wind parks

Offshore wind farms will play a key role in the energy supply by renewable sources. In Europe, especially in the North Sea, the number of installations of groups of wind turbines is steadily increasing [17].

Dillinger Hütte GTS is mainly involved by deliveries of plates used for the foundation by mono piles and tripods. This steel grades have typically a minimum yield strength of 355 MPa (e.g. S355 ML or S355 G9+M) in rather high thicknesses of up to 100 mm. Depending on the design, CVN impact tests have to be performed at –40 °C in mid thickness or at –50 °C in quarter thickness position. Such requirements are mastered by the application of leading steelmaking technology, TMCP utilization on high power rolling stands with additional ACC- or HACC-process.

High capacity offshore installation vessels are required for the erection of the wind turbines. For the jack-up vessel Seabreeze plate of grade S460G2+M with a thickness between 60 mm and 100 mm were delivered. CVN impact tests with a minimum of 60 J were required at –40 °C for subsurface and mid thickness position. Figure 18 shows the relative frequencies for the two testing positions. Even though all the results comply with the requirements, a certain decrease of the CVN impact energy from the subsurface to the mid thickness position can not be avoided for such plate with rather high thickness.

3.6 Penstocks

Not only but also for penstock application, DILLIMAX 500ML [18] fine grained high strength TMCP steel plates with a minimum YS of 500 MPa were developed. It is characterized by high toughness and strength combined with a lean chemistry. CVN impact values are usually required at –50 °C. For diverse penstock projects, plates with a thickness of up to 70 mm were delivered.

4 Summary

The paper highlights the requirements, the technological status and utilization of modern heavy plates.

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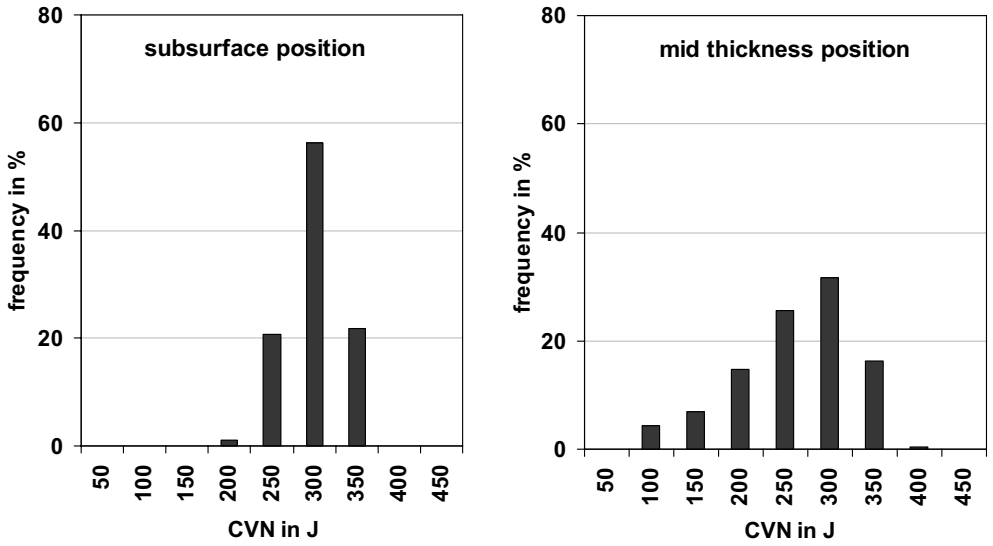


Fig. 18. CVN impact energies at –40 °C in transverse direction at subsurface and mid thickness positions for grade S460G2+M with thicknesses between 76 mm and 100 mm.

Fig. 18. Propriétés de résilience à –40 °C sens travers en peau de tôle et à mi- épaisseur pour un acier de grade S460G2+M d'épaisseurs comprises entre 76 mm et 100 mm.

An outline of the production facilities is given. As a central element to achieve high-class requirements aspects and parameters of the metallurgical design are presented.

The attainable level of properties is steadily growing by the utilization of the very latest technology in combination with subtle steel and plate making concepts. The current status of utilization and recent achievements are outlined and illustrated by examples.

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