Journal of ASTM International, Vol. 5, No. 8
Paper ID JAI101777
Available online at www.astm.org

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Accelerated Cooling of Steel Plates: The Time Has Come

ABSTRACT: The accelerated cooling of steel plates is an already standard process that increases the competitiveness of this product and their users, as it allows the adoption of a leaner alloy design and the development of new mechanical property combinations with improved weldability. The maximum cooling rate achievable under industrial conditions depends on plate thickness, from 80°C/s (10 mm) to about 1°C/s (80 mm), in order to assure minimum temperature gradients along plate thickness and greater uniformity of mechanical properties. The main process variants of this process apply cooling over different temperature ranges: interrupted accelerated cooling, between 800 and 500°C, and direct quenching, between 900 and 200°C. In the first case it is aimed at a microstructural grain refining effect; in the latter one a fully martensitic microstructure is desired. The advantages promoted by these new process routes are already benefiting the main fields of application of heavy steel plates, like shipbuilding, civil construction, linepipes, penstocks, and so on. This paper is a brief status report about this technology and its future developments.

KEYWORDS: plate rolling, accelerated cooling, thermomechanical controlled processing, microalloyed steels

Introduction

The advent of controlled rolling of microalloyed steels in the 1960s has allowed the reduction of the equivalent carbon value of structural plates without affecting their mechanical characteristics, as the alloying effects were substituted by an intense grain size refining. A finer grain simultaneously increases yield strength and toughness, but its effect is not so intense over tensile strength. This fact limits the use of leaner alloy designs [1–3].

The next step in this evolution was the development of accelerated cooling of plates with water immediately after its hot rolling process. However, this metallurgical tool became widely available only in the beginning of the 1980s, as several complex technical problems were solved at that time through an intense research and development program developed by several steelworks, mainly Japanese [4]:

- Assurance of good flatness in the rolling stock in order to avoid irregular water build-ups;
- Total suppression of rough surface scale in order to keep a uniform cooling rate;
- Adequate automation resources to maintain enough precision and uniformity in the rolling stock temperature before the application of accelerated cooling;
- Development of control systems of water application that keep consistent and uniform cooling rates along the entire rolling stock.

Nowadays the "use of water as an alloy element" is an acclaimed technology, as the dissemination of plate accelerated cooling lines all over the world has shown in the past 25 years. This process allows the development of tailored microstructures according to the specific mechanical characteristics required for a given application. In addition, it allows an extra reduction in the alloying content and, eventually, it can ease the controlled rolling process, allowing the increase of its finishing temperature. This measure not only increases the productivity of the plate mill line, but contributes to improve the final product flatness as well.

Manuscript received April 11, 2008; accepted for publication July 15, 2008; published online August 2008.

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TABLE 1—*Historical evolution of the controlled rolling and accelerated cooling processes, as well as the strengthening mechanisms and technical standards associated to them. Legend: SHT=Sumitomo High Toughness; TMCP=Thermomechanical Controlled Process with Accelerated Cooling [1].*

Year →	1960	1965	1970	1975	1980	1985	1990	1995	2000
	Controlled rolling		Two-phase region rolling					R & D for ultra-fine grain steel	
	Low temperature rolling			SHT process					
Thermomechanical processes					Accelerated cooling				
			Low reheating temperature rolling						
							Direct quenching		
							Modeling studies for hot rolling processes		
Strengthening mechanisms	Grain refinement		Deformation strengthening			Strengthening due to Martensite or Bainite			Ultra-fine grain refinement
			Transformation strengthening						
Technical standards						ASTM A841 (TMCP Steel)			
								JIS-SN (Building use)	

Basic Metallurgical Aspects of Accelerated Cooling

The historical evolution of controlled rolling and the accelerated cooling process (also known as Thermomechanical Controlled Processing—TMCP), as well the associated metallurgical mechanisms, can be seen in Table 1 [1,2]. The basic objective here is to get steel products not only with higher and higher strength, but with good toughness as well, and not forgetting improved processability characteristics, like easy welding.

The several process variants of the accelerated cooling of plates are shown in Fig. 1 [3–6]:

- Interrupted Accelerated Cooling: It starts just after the finish of hot rolling and ends at an intermediate temperature, then followed by air cooling. This is the most common case, where plate cooling is generally applied between 800 and 500°C under rates between 5 and 80°C/s.
- Direct Quenching: In this case plate cooling is more intense, ending at lower temperatures and generally promoting the formation of a full martensitic microstructure. Cooling generally starts at 900°C and ends at 200°C, under rates from 5 to 60°C/s.
- Direct Quenching Plus Auto-Tempering: This approach of direct quenching uses plate recalescence (that is, the surface reheating following accelerated cooling due to the heat flow from its core that is still hot) to promote a direct tempering to the product.

Figure 2 shows the effect of these process variants over microstructure and mechanical properties of a NbV microalloyed steel. The replacement of a conventional normalizing heat treatment by the interrupted accelerated cooling decreased plate grain size from 8–9 ASTM units to 10–11 ASTM units, changing the microstructure from ferritic-pearlitic to a mixture of ferrite, pearlite, and bainite. The use of direct quenching decreased even more grain size, to 11–12 ASTM units, and produced a microstructure constituted of bainite, martensite, and ferrite [3].

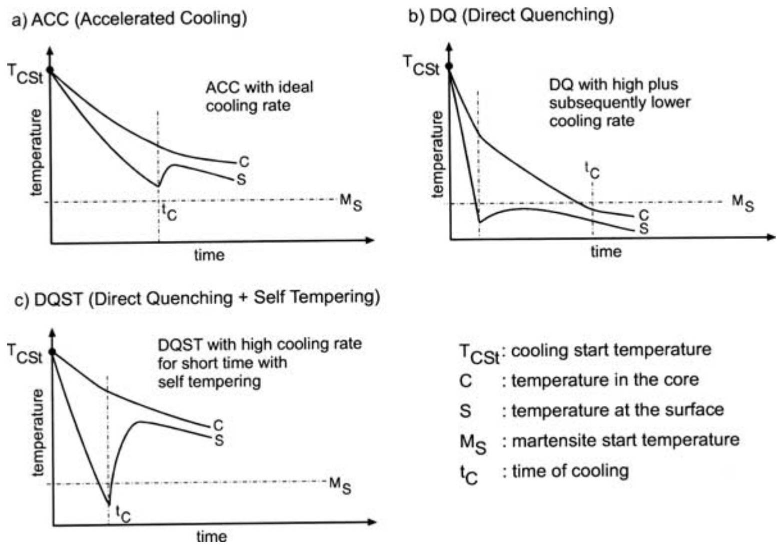

FIG. 1—*Variants of the plate accelerated cooling treatment: (a) interrupted accelerated cooling; (b) direct quenching; (c) direct quenching plus auto-tempering [3].*

The use of accelerated cooling is also beneficial in the production of extra-heavy plates. The rolling process of such products has become more problematic nowadays, with the end of the production of slabs using the ingot casting-slabbing mill route. Now slabs are exclusively produced through continuous casting, and so this as-cast semi-product normally shows limited thickness—generally 250 mm maximum. So it is impossible to produce plates with a thickness superior to 80 mm through the conventional hot rolling process, keeping the minimum hot reduction ratio required to assure internal soundness in the finished product, that is, 3:1 [7]. The grain refining promoted by direct quenching is one of the several approaches available to compensate for the lack of hot reduction degree [1].

Accelerated cooling can also be applied in plates produced by Steckel Mills. However, in that case, cooling rates during hot rolling can be slower in order to allow the rolling of thinner gage plates using heated coilers. This can be compensated for through the use of the so-called High Temperature Processing (HTP) of high-Nb (up to 0.1 %) steels associated with accelerated cooling.

Heat Transfer During Accelerated Cooling of Plates

Cooling rates in excess of 100°C/s are easily achieved using modern cooling equipment. However, maximum cooling rates for acceptable metallurgical properties in the plate are inversely proportional to its

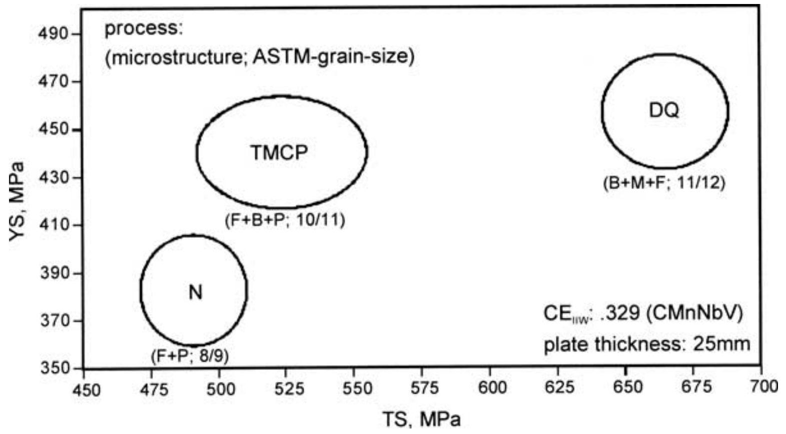

FIG. 2—*Effects of production route over the yield and tensile strength of a NbV microalloyed 25 mm steel plate. Legend: N=normalizing; TMCP=interrupted accelerated cooling; DQ=direct quenching; F=ferrite; P=pearlite; B=bainite; YS=yield strength; TS=tensile strength;* CE_{IIW}*=carbon equivalent calculated according to the formula of the International Institute of Welding [3].*

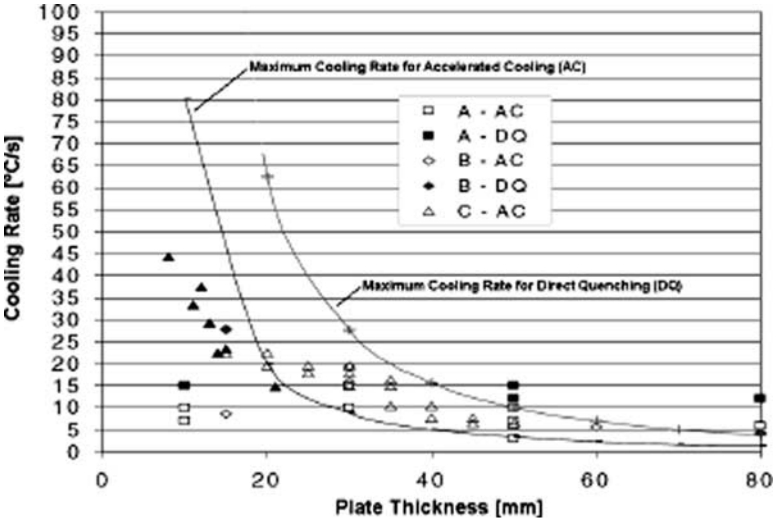

FIG. 3—*Cooling rates requested by some plate producers (A, B, and C) during the specification of accelerated cooling (AC) and direct quenching (DQ) equipment. The graphic includes the maximum cooling rate advisable for accelerated cooling/direct quenching in function of plate thickness [4].*

thickness. Excessive cooling rates applied in a thick plate lead to the development of large temperature gradients between plate core and surface which can promote uneven microstructures and residual stresses along plate thickness, resulting, respectively, in poor mechanical performance and flatness problems. For thick plates, heat conduction through thickness is the limiting factor to the cooling rate; in the case of thin plate, heat transfer at the surface is the critical factor [4,6].

It is widely known that heat transfer coefficient during plate cooling varies with decreasing temperature, which obviously affects the achievable cooling rate. Above approximately 450°C a stable steam layer forms on the plate surface, which the water jets must penetrate in order to achieve high cooling rates. Below this temperature this steam layer breaks down and the heat transfer rate increases. At temperatures below 150°C boiling ceases and the heat transfer rate decreases again [4].

Accelerated cooling is applied between 800°C and 500°C, that is, in the temperature range where there is a stable film boiling. In this case it is advisable not to break the steam layer in order to keep heat transfer coefficients fairly constant with temperature. For its turn, direct quenching is carried out between 900°C and 200°C, passing through all regimes of film boiling. In this case plate cooling must be fast enough to promote a fully martensitic structure. If this condition is satisfied, the alteration in the cooling rates do not represent a major control problem. The real problem is to achieve sufficiently high cooling rates over a wide thickness range [4].

Figure 3 shows the cooling rates that are being requested by plate producers when they specify accelerated cooling/direct quenching equipment according to the product gage. This figure includes the maximum cooling rate values in the function of plate thickness that are metallurgically feasible for application when using these processes [4].

The Market of Steel Plates Processed via Accelerated Cooling

ASTM included accelerated cooling as a standard process for production of steel plates for use in pressure vessels as early as 1985 in its A841 technical standard. The ASTM recognition promoted the rapid commercial adoption of this new process. A new recognition occurred in 1993, when ASME accepted the use of accelerated cooled plates in its code for pressure vessels. At this time, accelerated cooling is widely accepted for the production of steel plates with a thickness up to 100 mm [1]. Table 2 shows typical applications and mechanical strength levels for steel plates produced through accelerated cooling. Nowadays about 20 % of steel plates rolled all over the world use this production route; this share doubles in the case of high strength steels, that is, plates with tensile strength over 490 MPa [2].

Shipbuilding—The use of accelerated cooled plates quickly expanded in this field; besides that, it makes feasible the use of high strength steels in this specific application. This product increased the

TABLE 2—*Requirements in terms of thermomechanical controlled process with interrupted accelerated cooling (TMCP) or direct quenching (DQ) for different applications and mechanical strength levels.*

	Tensile Strength [MPa]				
Application	490	590	690	780	950
Shipbuilding	TMCP				
Offshore platforms	TMCP	TMCP			
API pipes	TMCP	TMCP	TMCP		
Civil construction	TMCP	DQ	DQ	DQ	
Bridges	TMCP	DQ	DQ	DQ	
Penstocks	TMCP	DQ	DQ	DQ	DQ
Low temperature tanks	TMCP	DQ			
Cryogenic tanks	TMCP*[a]		DQ**[b]		
Heavy machines	TMCP	DQ	DQ	DQ	DQ

[a] Legend: *=Low Ni.

[b] Legend: **=9 % Ni [4].

competitiveness of shipyards, as this kind of material allows the reduction of the dimensions of ship components without impairing its performance, decreasing manufacturing and operational costs. The use of accelerated cooling also allowed the reduction of C and alloy elements contents in steel, increasing significantly its weldability. As it is widely known, welding is an expensive process that can be responsible for more than 50 % of the total production costs of a ship [8]. The use of accelerated cooled plates with a yield strength of 315 MPa or 355 MPa began in 1982; today they represent more than 50 % of steel used in a ship. Versions still more stronger, with 390 MPa yield strength, began to be marketed in 1985; nowadays they constitute 30 % of steel materials present in a ship. Or, to use other words, 80 % of the steel plates used in a ship are processed through accelerated cooling. This process also promoted the development of a new product for use in oil tanker hulls which show very high toughness. This kind of plate can avoid the wrecking of such vessels, which can lead to catastrophic ecological disasters. In this specific case accelerated cooling is applied early, during plate rolling start, in a quick and intense way, promoting the austenite to ferrite transformation in the surface layers of the rolling stock. After the application of accelerated cooling, plate surfaces reheat along the remainder of the hot rolling process, allowing the deformed ferrite to recrystallize with the consequent formation of a microstructure with ultra-fine grains and a well-developed crystallographical texture. This ultra-refined microstructure has high toughness, even after the plastic cold working that can arise from a hull collision [1,2].

Civil Construction—In Japan, approximately 10 % of steel plates used in this application are submitted to accelerated cooling, especially the 780 MPa tensile strength grade, a product with high weldability used in the construction of bridges with long spans and high buildings. In that country, steel plates used in civil construction must show low yield ratio in order to constitute structures with a "plastic reserve" that are able to endure the action of frequent earthquakes. In this case the effect of accelerated cooling is associated with a balanced chemical composition in order to promote the formation of a dual phase microstructure constituted of ferrite and bainite/martensite, which shows the required values of yield ratio. In some cases it also used strengthening through copper precipitation in order to reduce even more the carbon content of the alloy. Accelerated cooling is also beneficial in this case, as it intensifies the response of the subsequent aging treatment. A quick cooling just after the rolling finish suppresses copper precipitation in austenite during the subsequent air cooling of the plate, which does not harden steel. So a higher amount of copper remains soluble and will precipitate only during subsequent aging, effectively promoting an increase in plate mechanical strength [1,2].

API Pipes—Figure 4 shows the historical evolution of the alloy design used for API steel pipes along the past 40 years. One can note that the use of controlled rolling, which was lately complemented by accelerated cooling, allowed a progressive reduction in the carbon content of steel, and simultaneously increased mechanical strength. As a matter of fact, the yield strength of API pipes increased from 360 MPa (API grade X52) to 820 MPa (API grade X120) along this time span [3–5]. This mechanical strength increase allowed reduction of pipe thickness—for example, an API X120 pipe is 39 % thinner than an equivalent API X70 pipe. Thinner pipes are lighter and so its transportation is easier and cheaper; the civil

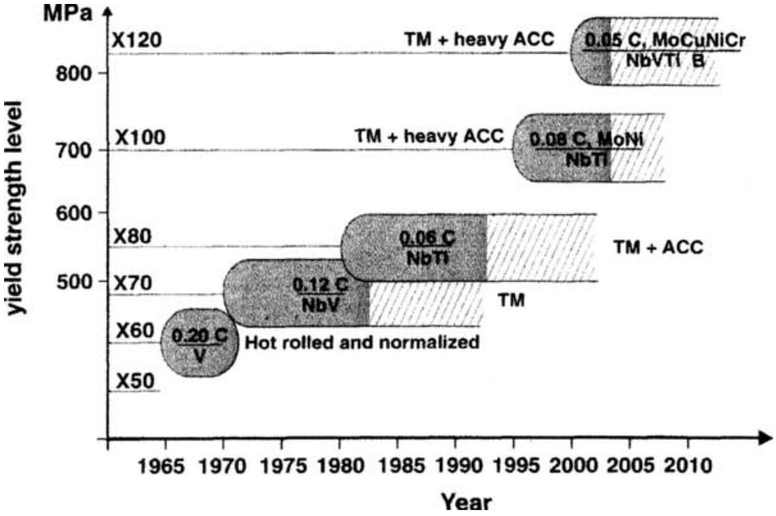

FIG. 4—*Historical evolution of the alloy design and thermomechanical rolling processes used for the production of steel plates for API pipes. Legend: TM=thermomechanical treatment; ACC=accelerated cooling [8].*

works needed for pipe installation are smaller. The area to be welded is also smaller, which contributes to reducing the cost of this expensive process, which is also decreased due to the lower carbon content of the accelerated cooled steel plate. The cost savings achieved by the use of accelerated cooling in this kind of product can amount to more than US$ 40/tonne [6]. Besides that, the use of accelerated cooling decreases the available time for carbon diffusion during austenite transformation, reducing the segregation of this element and minimizing the formation of hard constituents which are weak points for hydrogen-induced cracking (H.I.C.) in pipes that conduct oil with a high H_2S content. So this new process route is very effective for the production of API grade steel plates with higher mechanical strength and H.I.C. immunity [3–5,9].

Penstocks—This is an application that requires extra-heavy steel plates with maximum levels of mechanical strength. Up to this moment, plates with tensile strength of 780 MPa are being used, but there is a proposal to increase this value up to 950 MPa in 100 mm thick plates to comply with higher water pressure that prevails in big hydroelectric power plants. This is a typical application for the conjugated use of controlled rolling followed by direct quenching. These plates cannot be produced in conventional quenching and tempering lines, as cooling rates available in such a route are not enough to guarantee the minimum level of mechanical properties required through plate thickness. Besides that, the austenitizing temperature used in these lines, between 900 and 950°C, is not high enough to promote full Nb solubilization, and so this element cannot contribute to hardenability as it does during direct quenching, where slabs are reheated over 1200°C. Besides that, austenite conditioning immediately before direct quenching shows ideal features for this case, as a plate will have refined grains in its surface and rougher grains in its core. In other words, this plate will have a surface with lower hardenability, where cooling rates show maximum values, and a core with higher hardenability, where heat transfer is more difficult. In such a way there is an equalization of mechanical properties through plate thickness.

Conclusion

Now, almost 30 years after the industrial implementation of the interrupted accelerated cooling and direct quenching of steel plates, these processes can be considered fully mature, as they were adopted by many steelworks around the world and by several product technical standards. Nowadays the intrinsic benefits associated with the use of such processes—optimization of alloy content and new combinations of mechanical properties—represent extra advantages no longer, but rather are quickly becoming the state-of-the-art for high quality steel plates.

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