

Surface Hard Zone Phenomenon in TMCP Line pipes for Sour Service: A State of the Art Review

Ali Smith
Rina Consulting-CSM
Via Di Castel Romano 100
Rome, 00128
Italy

Carlo Spinelli
ENI
Piazza Ezio Vanoni 1
San Donato Milanese
Italy

ABSTRACT

Carbon steel line pipes for sour service are required to exhibit hardness levels less than 250 HV10. The hardness of the inner pipe surface is especially critical, since sulphide stress cracking (SSC) may initiate at hardened surfaces. In recent years, high profile failures in sour environments were attributed to the presence of identified hard zones on TMCP pipe inner surfaces, and located far from welds. To help define the SSC limits of such material it is critical to know how these areas form.

Based on these considerations, the European Pipeline Research Group has launched at the end of 2017, a research project aiming to reproduce these hard zones via lab scale TMCP, aiming to identify the root cause.

This work deals with the first phase of this project, namely a state of the art review covering potential hard zone formation mechanisms in TMCP pipes. From the analyses performed, several mechanisms were found to be potentially relevant for hard zone formation during TMCP plate manufacture. First, possible carbon contamination from the casting phase. Second, the use of intense accelerated cooling equipment. Third, the effect of oxide scale in enhancing cooling power with standard accelerated cooling.

Key words: Hard spot, hard layer, TMCP, Line pipe, sour service

INTRODUCTION

Carbon steel line pipe manufactured from plates via thermo-mechanically controlled rolling (TMCP=Thermo-Mechanically Controlled Processing) has been successfully used in sour service applications for many years.¹ Resistance to SSC is traditionally obtained by keeping hardness below 250HV10 and obtaining a fine and homogeneous microstructure. Additionally, resistance to SSC and

HIC is achieved by the use of inclusion shape control, lean steel chemistries, and process control during casting.¹ Moreover, pipes are also qualified for specific sour or a range of sour environments via SSC and HIC fitness for service tests as specified in ISO15156-2.² Nevertheless, recent, high profile SSC failures of TMCP pipes have occurred.³ These were attributed to crack initiation at hard zones located on the inner surface of the pipes in base metal i.e. far from welds. These hard zones were located at a depth of less than 1 mm from the pipe inner surface, making their detection difficult by standard QA/QC.

Based on these considerations the European Pipeline Research Group (EPRG), has instigated a research program on this crack initiation phenomenon, aiming to identify the root cause. The current contribution describes the outcomes of the first part of the EPRG program, namely a literature review covering potential hard zone formation mechanisms. Thus, after obtaining a basic description of surface hard zone characteristics and general indications regarding the causes, a more detailed assessment is made of relevant manufacturing steps, identifying the most likely mechanism(s). Finally, for each of the mechanism(s) identified, the necessary conditions needed for hard zone production are given, supported by calculations made using a published hardness model.

LITERATURE REVIEW

Current knowledge of hard zones

From initial discussions within the EPRG a general picture of the hard zone phenomena was first established as a starting point for the literature review. This is summarized in table 1.

Table 1
Hard zone knowledge as of end 2017 according to EPRG

Type of Pipe	Hard zone distribution	Geometry	Hardness (HV10)	Suggested factors
TMCP	Random spots on “at least” pipe inner surface and in base metal	Width + Length in range few tens of mm Depth < 1mm	Above 250 HV10	Accelerated cooling during plate hot rolling Local chemistry variations
TMCP	Continuous layer in base metal near pipe inner surface	Near surface layer (< 1 mm depth) covering entire plate		

As can be seen from table 1, these hard features are sometimes referred to as spots or layers, and occur in the base metal. Here it should be noted that the term spots used in this paper does not relate to those mentioned in API 5L section H 5.2, covering hard spots (considered a defect if > 50 mm in size) with hardness above 250 or 275 HV10.⁴

From table 1, it can be seen that some clues as to the origin of hard zones point towards accelerated cooling of the plate in the rolling mill and/or some sort of unspecified surface chemistry change. In addition, the two indicated geometries above would appear to hint at two different mechanisms.

From the published literature hard zone characteristics were first discussed in two papers from 2016 and 2018.^{5,6} These references declare that hard spots are a rare but unavoidable phenomenon in the production of heavy plates. The hard spots were declared as having a bainitic-martensitic structure.⁵ By means of an NDT inspection program on 300000 mt of plates, it was shown that only 0.25% of plates contained hard spots (> 250HV10). Moreover the hard spots could be removed by slight grinding i.e. indicating a thin surface affected depth.^{5,6} Also, for NDT calibration purposes the authors described the

use of carburized plates (carburized slabs, which were reheated and TMCP rolled), with surface hardness areas in the range of 250-300HV10.⁵

Another recent paper from 2018 declared that recent cracking incidents with high pressure H₂S were initiated at hard zones having a bainitic/martensitic structure.⁷ These hard zones were present up to 1 mm depth from the pipe ID. Moreover, beyond this depth the hardness was reduced to nominal levels and the microstructure was representative of the linepipe steel grade. Finally, in certain vintage pipes produced in the 1950s and 60s hard spots of martensite with 350HV10 were found.⁸ These spots were caused by uncontrolled water cooling between rolling passes (before TMCP was developed), and presumably aggravated by the richer chemistries used at the time.

Surface local chemical variations during TMCP plate manufacture

This section deals with possible surface chemical changes occurring during TMCP plate manufacture (which may eventually cause hard zones in the pipe). From the review exercise, segregation phenomena were first analysed and then excluded, leaving carbon pick-up during continuous casting as the most likely candidate. The steel may pick-up carbon from a number of external sources as illustrated by figure 1.

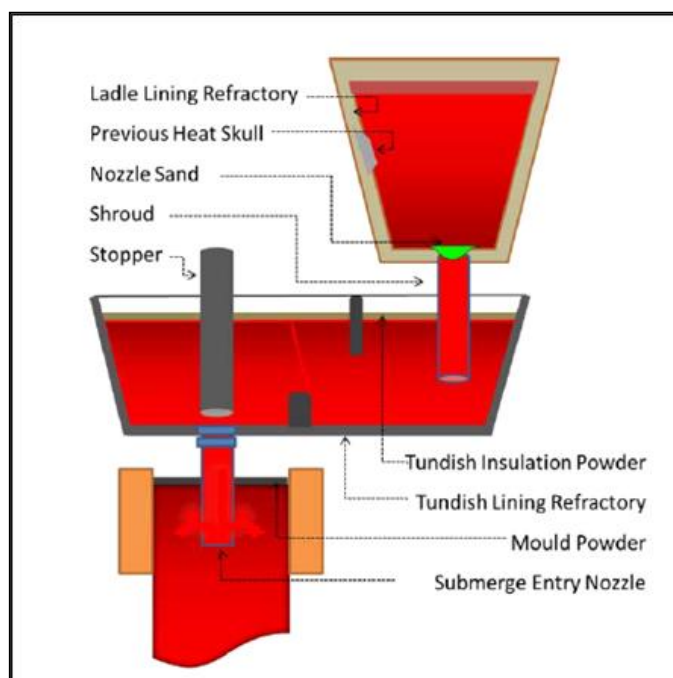


Figure 1: Potential sources of carbon pick-up during continuous casting of steel slabs.⁹

These sources of contamination include refractories, ladle nozzle sand, tundish insulation powder, and the mould powder.⁹ Table 2 summarises these sources and the amount of carbon that can be picked-up into the steel, as obtained from literature references.

Table 2
Sources of carbon-pick up into steel during continuous casting and the estimated increase in steel carbon content

Source	C level in source (wt%)	Enters liquid or solid steel	Location of enrichment	Estimated increase in steel carbon content
Refractories e.g. MgO-C ladle	Variable	Liquid	Homogeneous	3-10 ppm ^{9,10}
Ladle nozzle sand	e.g. 1.5%	Liquid	Homogeneous	1 ppm ⁹
Tundish insulation compound	Variable	Liquid	Homogeneous	4-10 ppm ⁹
Mould powder	3-14%	Liquid	Homogeneous	3-200 ppm ¹¹
Mould powder	3-14%	Solid	Steel near surface (≤ 1 mm)	Estimated increase at 0.5 mm depth : 0.04 wt% - 0.13wt% (400 ppm – 1300 ppm) for steels with 0.04 to 0.5 wt% C. ¹¹

As can be seen from table 2 the largest potential increase in carbon level in the steel during casting is due to the mould powder. For the case of the solid steel shell that forms in the mould, the process of carbon entry occurs in the following way. First the mould powder melts and a slag is formed. A carbon particle may then be picked up in the solid steel shell, either by contact with molten slag at the meniscus, or at the zone between mould wall and steel solid shell.¹¹ Also, subtle variations in casting speed and caster alignment can result in disruption within the meniscus, and a wave forming, which can result in mould powder being transported further down the side of the mould to interact with the solid steel. Finally, the carbon in contact with the solid steel then diffuses into the steel surface causing recarburization.¹¹ From table 2, resulting enrichment levels in the solid steel surface range from 0.04-0.13 wt% of carbon. Moreover, the enrichment occurs in surface of the solid steel cast slab to a depth of about 1 mm. An example of such enrichment based on experimental and modelling work in the literature applied to a 0.5 wt% carbon steel is shown in figure 2.¹¹

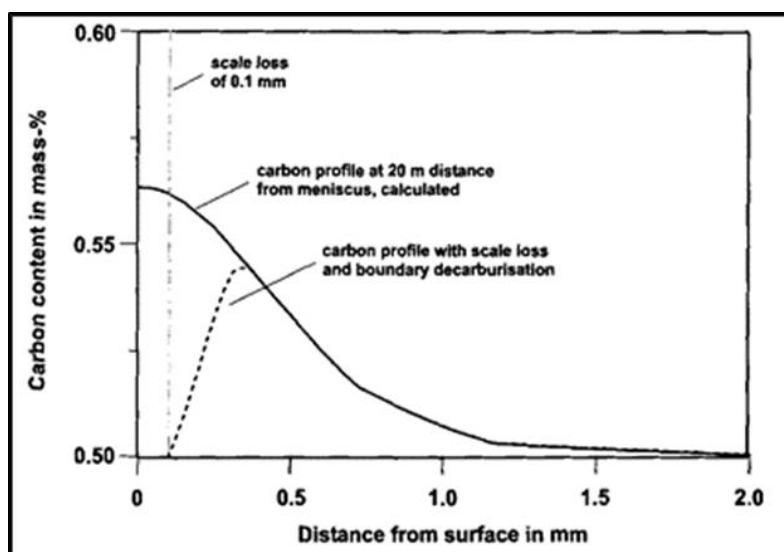


Figure 2: Predicted carbon content picked up in solid steel versus depth (in wt%) at 20 metres from the meniscus (i.e. after final cooling) during continuous casting.¹¹

From figure 2, the final carbon content after slab cooling reaches a predicted maximum at around 0.3 mm depth, when scale loss and decarburization are considered. Moreover, this peak carbon content is 0.54 wt% versus a nominal level of 0.5 wt%. In addition, it can be seen that the maximum intrusion depth is about 1 mm.

Overall from this section it can be argued that mould powder carbon contamination may introduce significant carbon into the steel surface. If this carbon is not diluted by diffusion, and cooling rates are sufficient, then hard zones could potentially form after hot rolling and accelerated cooling.

Accelerated cooling during TMCP plate production

This part of the review focuses on the potential role of the accelerated cooling step on hard zone formation in TMCP plates. Figure 3 shows the TMCP process where steel plates are subjected to accelerated cooling after hot rolling.

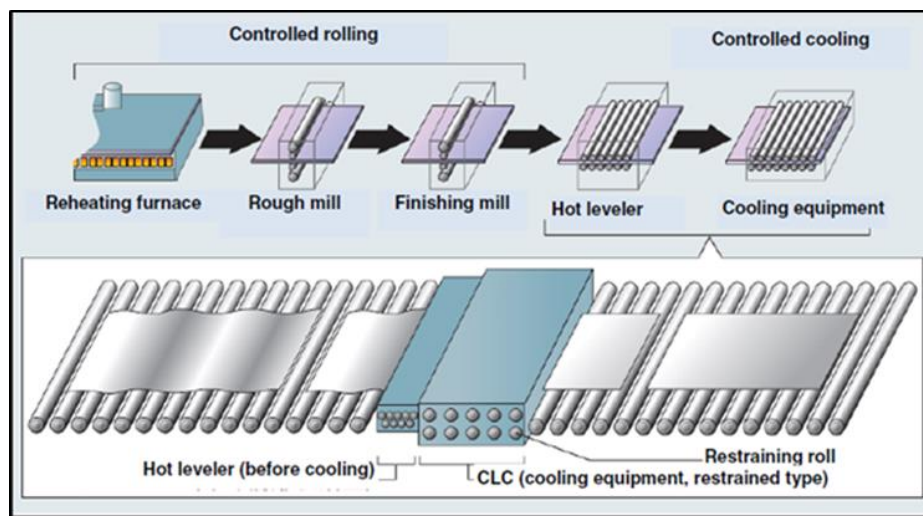


Figure 3: Generic hot rolling mill layout for TMCP production of steel plates.¹²

As can be seen, the slab is reheated, then subjected to roughing followed by finish rolling. After going through the hot leveler the steel plate is subjected to water spray cooling (accelerated cooling) which transforms the refined austenite structure into a microstructure desirable for the final application e.g. fine ferrite with bainite for linepipe applications, depending on the grade. During accelerated cooling there is the possibility of inhomogeneous cooling in different directions. Over cooling the plate from the top or bottom (the thickness direction) can occur if the water flow rates are not properly controlled. This can lead to top or bottom surface distortion and a higher surface hardness. Over cooling of the ends and edges (longitudinal and transverse directions) due to water accumulation at plate edges or due to splashing, can lead to distortions and hardness increases.¹³ These over cooling problems are well known and are avoided by careful design or optimization in the steel mill commissioning phase.^{12,13} Accelerated cooling systems have developed over the years leading to the introduction of advanced cooling systems which give reduced temperature variation over the plates surfaces during accelerated cooling.¹² This allows production of plates guaranteeing minimal strength variations, as well as reduced problems with flatness. Such advanced cooling systems achieve better temperature homogeneity, for example by promoting higher heat transfer over a wider temperature range compared to conventional systems. For the ordinary systems, at high temperatures the heat transfer occurs through a film of steam on the plate surface. As the temperature is lowered an unstable transition zone is reached where