Microstructural characterization and production of high yield strength rebar

E. Mansutti, G. Luvarà, C. Fabbro, N. Redolfi

Various technical standards from all over the world set out the mechanical and chemical characteristics for high yield strength rebar. High yield strength rebar - as defined in this study – is applied to all concrete reinforcement steel grades which require a minimum yield strength of 600MPa. The standards concerning rebar production were reviewed in order to select all the possible grades that come under the above-mentioned definition.
This research project aims to determine if by applying an in-line quenching and self-tempering process, the technological requirements for high yield strength rebar, as specified in the standards, can be met, in order to optimize the chemical composition and save on alloying elements. The work can be divided into two different phases. The preliminary phase took place in the metallurgical laboratory of Danieli's research center and the second phase in an industrial plant. Tests done in the laboratory set out to evaluate the effect of quenching and chemical composition on the rebar's final mechanical properties and microstructure. The purpose of the industrial-scale tests was to evaluate the potential of DANIELI's in-line quenching and self-tempering process, referred to as QTB (Quenching and Tempering Bar process), applied to high-strength steels. At the end of the lab tests, three different chemical compositions were selected, deemed suitable for the production of high yield strength rebar. In the industrial-scale tests it was then possible to evaluate the performance of the QTB process in the production of high yield strength rebar in terms of operating flow rates / pressures, optimized chemical compositions, productivity and process stability.

Keywords: Rebar - Yield Strenght – Quenching - Microstructure

INTRODUCTION

The application of high yield strength rebar is provided for in various technical standards from all over the world, such as the US, Russia, Korea and Japan.
Russia, for example, introduced the concept of high-yield rebar (980MPa) back in 1982, which was then developed further in GOST 10884 issued in 1994.
The mentioned GOST standard takes advantage of the known effect of silicon on enhancing elastic limit, allowing it to be added up to a maximum of 2.3% so that the steel can be included in the At1200 class (or class VI, considering the former standard), which corresponds to a minimum yield strength of 1200MPa.
Less indicative, however, is the recent Korean standard that for the SD700 class only specifies a limitation regarding equivalent carbon (CeqIIW = 0.63).
In Japan in 1993 a research project was carried out, referred to as "New RC Project", which was then incorporated into the National Building Code [1] [2].
The US has published the most recent ASTM standards on this subject. Both standard A615/A615M and A706/A706M introduced "Grade 80", which not only requires minimum yield stress values but also particularly high minimum UTS values (725MPa for standard A615 and 690MPa for A706). In addition, the A706 is more demanding in terms of Rm/Rp ratio, maximum carbon content and Ceq; in practice this makes it more complicated to apply on-line heat treatments in rolling mills, requiring greater attention to be placed on chemical composition. It is also important to bear in mind that compared to European standards, US standards are more stringent in terms of statistical reliability of technological values, requiring rebar producers to guarantee yield strengths that are significantly higher than the minimum requirements of the standard.
Again, in the US market standard A1035 provides for the possibility of producing high-tensile corrosion-resistant rebar through high chrome content (around 9%) and by controlling the final microstructure by taking advantage of the new technologies for in-line heat treatments [3].
It is interesting to note that in the US market various rebar producers are pushing for the introduction of high yield-strength grades (such as proposing classes "100" and "125"), even if current market demand for this type of product is low.
In China there are no reference standards for equivalent grades, although some studies refer to the use of V-N microalloyed steels and ultrafine grained steels [4][5][6].

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COUNTRY	Ref. Standard	Maximum yield strength	Remarks
RUSSIA	GOST 10884-94	1200 MPa	High yield strength with addition of silicon up to 2.3%
UKRAINE	DSTU 3760-06	1000 MPa	-
JAPAN	“New RC Project 1993”	980 MPa	Also includes grades @ 1275 MPa but only for transverse reinforcement applications
USA	ASTM A1035-14	830 MPa **(120 ksi)**	High yield strength by controlling microstructure
KOREA	KS D3504-11	700 MPa	Ceq increase allowed up to 0.63
ENGLAND	BS 6744-01+ A2:09	650 MPa	Stainless steel rebar
INDIA	IS 1786-08	600 MPa	Microalloyed steel with maximum C_{eq} of 0.53
CHINA	GB1499.2-07	500 MPa	C_{eq} max 0.55

Tab. 1 – Overview of international standards for high-tensile rebar. Ceq as per IIW standard: (C+Mn/6+(Cu+Ni)/15+(Cr+Mo+V)/5.

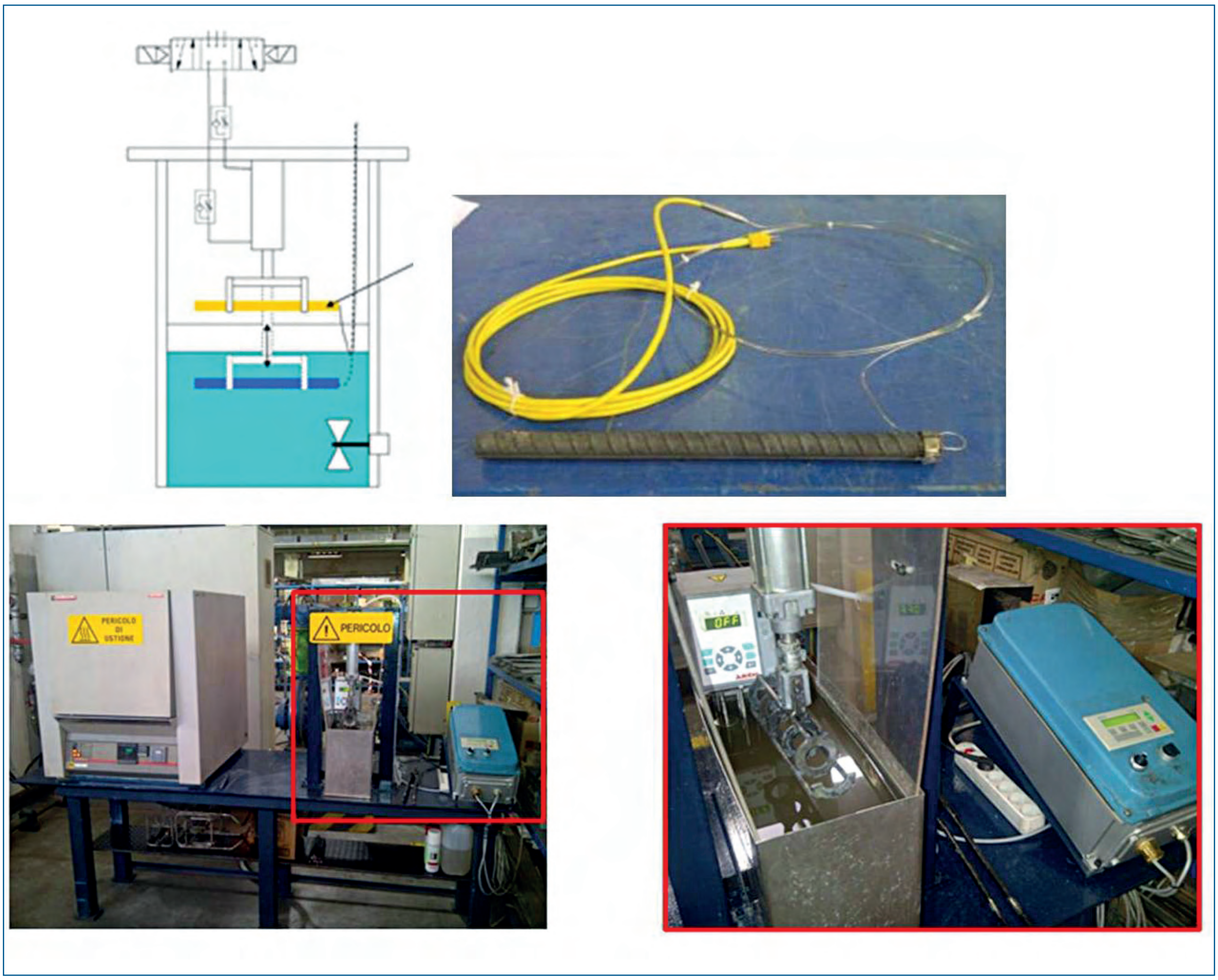


Fig. 1 – Diagram of a timed quenching system and example of a sample with a thermocouple attached to it (top). Photo showing the quenching station with heating oven and timed quenching system.

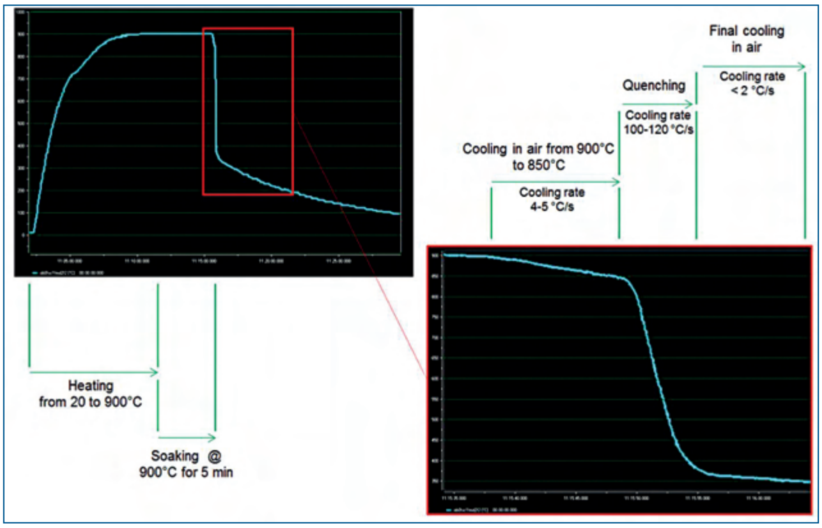


Fig. 2 – Temperature trend measured at the core of a DIA 16mm rebar during the test

Table 1 summarizes the main international reference standards for high yield strength rebar.
Civil engineering applications until now have been rather limited even if this type of rebar is promising as it simplifies the reinforcement of concrete [7].

GOAL

This study aims to examine the possibility of meeting the technological requirements specified in various international standards for high yield strength rebar, using the in-line quenching and self-tempering process, thereby optimizing the chemical composition with considerable savings in alloying elements.
Tests done in the laboratory set out to evaluate the effect of quenching and chemical composition on the rebar's final mechanical properties and microstructure.
The industrial-scale tests then evaluated the potential of DANIELI's in-line quenching and self-tempering process, referred to as QTB (Quenching and Tempering Bar process), applied to high-strength steels.

LABORATORY TESTS

In order to study the mechanical and microstructural properties of various rebars subjected to a quenching and self-tempering process, a device (suitable for different diameters) was set up to heat-treat samples of rebar that were previously fitted with thermocouples (Figure 1).
The system is made up of:
- Heating oven with inert atmosphere (Ar)
- Brine quenching tank with timed immersion system

For the experiment it was decided to use a DIA 16 rebar with a length of about 250mm.
Shown in Figure 2 is a representative trial heat cycle of a sample subjected to testing.
The experiment involved:
- Heating the sample to 900 °C
- Soaking it for 5 minutes
- Air cooling it down to 850°C and then quenching it (from 1 to 5 seconds)
- Interrupting the cooling process by self-tempering of the material surface, and final air cooling.

DIA 16mm rebars with three different compositions were selected for the experiment (see Table 2) in compliance with specific international standards.
The following three compositions were used:
- Composition#1 with medium carbon content and high silicon content;
- Composition #2 with low carbon content and medium Mn content;
- Composition #3 with high Mn content and medium Si content.

The aim of the experimental plan was to determine the combined effect of C, Mn and Si on hardenability and performance in terms of mechanical and microstructural properties. In particular the effect of a composition with lower Mn and higher C and Si contents (such as composition #3 for example), was compared to the other two chemical compositions with lower carbon and higher Mn contents.

LABORATORY EXPERIMENTAL PROCEDURES AND MATERIAL CHARACTERIZATION

Samples of each rebar composition shown in Table 2 were quenched at increasing immersion times from 1 to 5 seconds while the core temperature was continuously monitored. For each test both microstructural properties and mechanical strength were analyzed and measured.
To facilitate the comparison of results, before performing the tests, various heat treatments were considered to decide which one would be used to determine the same prior austenitic grain size for all the samples. This made it possible to use the same heat treatment (briefly described in the previous chapter) for all three steel grades studied.
The quenched rebar pieces were subjected to a tensile test to determine their mechanical properties.
Figure 3 shows a growing linear trend of yield strength up to a maximum of 1000 MPa for compositions #2 e #3,

Composition	%C	%Mn	%Si	%P	%S	%V	%Al	%Cu	%Cr	%Ni	N ppm	Ceq
#1	0.36	0.67	0.96	0.033	0.026	0.008	0.003	0.06	0.05	0.03	84	0.49
#2	0.22	0.98	0.18	0.018	0.015	0.003	0.004	0.28	0.10	0.08	117	0.41
#3	0.19	1.31	0.50	0.033	0.033	0.006	0.003	0.03	0.02	0.01	58	0.41

Tab. 2 – Result of the chemical analyses performed on samples from lots selected for the experiment; elements not shown on the table are present only in trace amounts. Ceq according to standard IIW: (C+Mn/6+(Cu+Ni)/15+(Cr+Mo+V)/5.

while composition #1 exceeds 1200 MPa.

On Figure 3 it can be noted that elongation diminishes along a linear path as quenching time increases, with all three steels following the same trend, while the decrease in Rm/Rp ratio is less marked.

Because of its higher carbon and silicon contents, chemical composition #1 is able to reach the required yield strength within a shorter quenching time. Moreover, even with higher carbon and silicon contents, ultimate elongation is not penalized for up to 3 seconds of quenching (which makes it possible to obtain a product with a yield strength of 980MPa).

Composition #2, which has lower C, Mn and Si contents, produces the lowest elongation value, even with relatively short quenching times (1sec).

On next page is reported a summary of the results for:

- Analysis of microhardness (HV0.3) within the cross-sectional area of a rebar subjected to different cooling times;
- Description of the microstructure observed at the core of the rebar with temperature measured at the end of immersion (thermocouple placed at the core of the rebar).

In general, a gradual increase is noted in the presence of rapidly cooled structures at the core of the rebar, and even completely hardened structures resulting from quenching times of between 2.5 and 3.0 seconds.

Compared to composition #2, the increase in Mn and Si for chemical composition #3 leads to a slight rise in martensite hardness at the end of the cycle (in both cases cooling time was 4”).

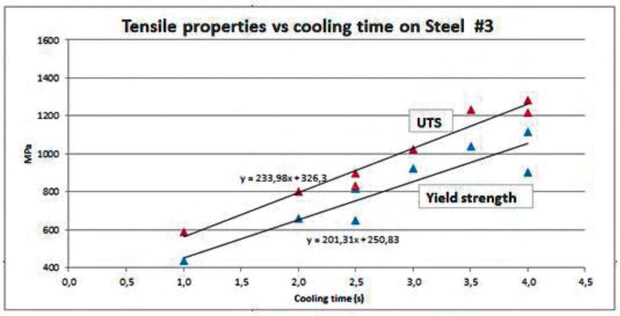
Increased material hardenability due to higher Mn and Si, together with the effect of tempering stability provided by the silicon, still leads to increased hardness within the cross-sectional area of a rebar quenched for the same amount of time.

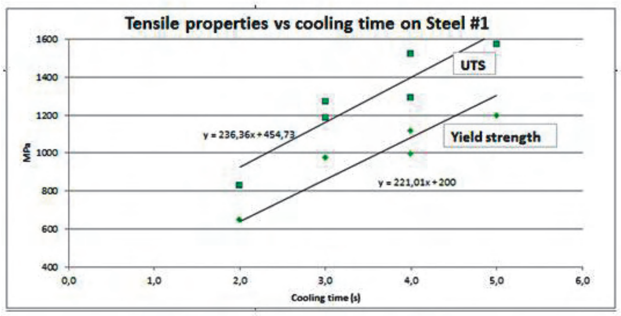
A comparison of the above results with those of chemical composition #1 show that the high C and Si contents, which ensure greater hardenability, make it possible to achieve complete hardening with shorter quenching times. The result obtained with a shorter quenching time (2 sec) and higher final temperatures (550 °C) is comparable to the performances of the other steel grades.

The strategy of using higher amounts of carbon and silicon while reducing the amount of manganese is only effective if managed properly through controlled cooling.

Steel	Cooling time [s]	Rp0.2 [MPa]	Rm [MpA]	Rm/Rp	A%	A5d %
2#	1.0	420	603	1.44	16	16
	2.0	600	888	1.48	6	3
	2.5	861	1053	1.22	10	9
	3.0	880	1005	1.14	8	7
	3.5	920	1118	1.22	5	4
	3.5	920	1132	1.23	6	5
	4.0	1068	1296	1.21	3	3
	4.0	1000	1329	1.33	4	3
3#	1.0	434	589	1.36	17	20
	2.0	660	803	1.22	12	3
	2.5	650	829	1.27	12	14
	3.0	920	1025	1.11	8	10
	3.5	1040	1234	1.19	9	9
	4.0	1114	1282	1.15	7	4
1#	2.0	650	830	1.28	15	16
	3.0	980	1188	1.21	10	11
	3.0	980	1276	1.30	8	9
	4.0	1000	1293	1.29	4	3
	4.0	1120	1527	1,36	7	5
	5.0	1200	1578	1.,32	5	5

Red n.: breakage outside calibrated lenght





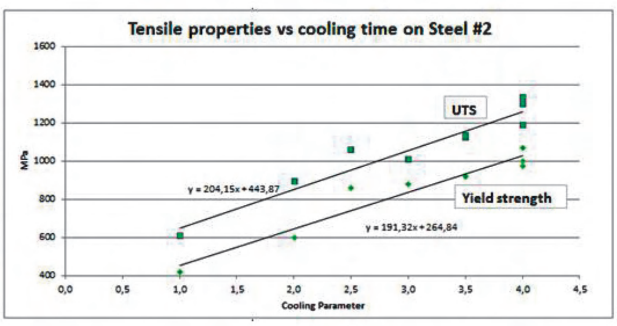
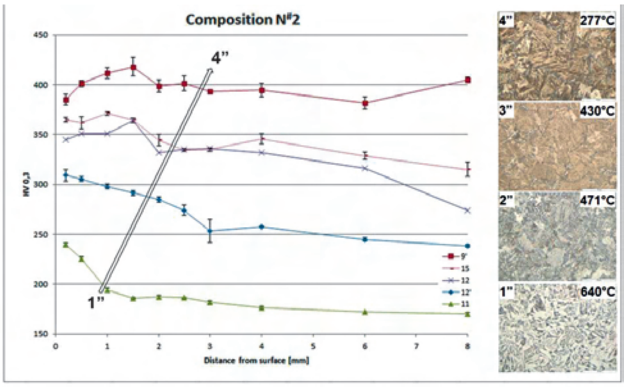


Fig. 3 – Change in mechanical properties as quenching time increases (right bottom). The measured mechanical properties are reported on the top right.

INDUSTRIAL-SCALE TESTS

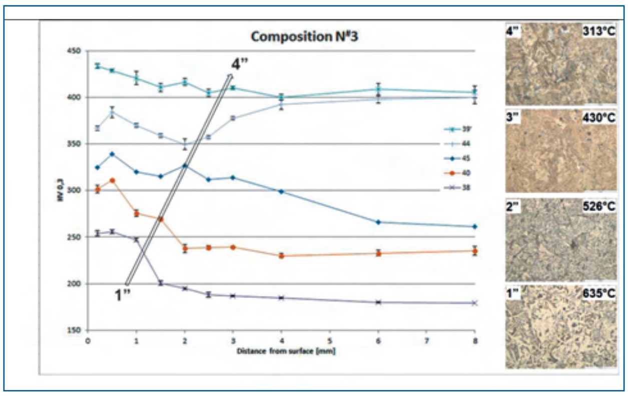
Following the results of the lab tests and in keeping with specific plant requirements, various tests were performed in a real plant to evaluate the capability of in-line heat treatment processes (QTB) in the production of high yield strength rebars.
These tests were essential in order to validate the results of the laboratory tests, overcome their limitations and simplifications and determine the stability of the in-line process in a real rolling mill.
Based on the results of the laboratory tests, an initial chemical composition was selected in order to ensure good material weldability.
Before running the tests, the technological parameters of the rolling mill were studied using the thermal/metallurgical software DLPP (Danieli Long Products Predictor), which was also used to evaluate the test results [8].
Figure 7 shows the heat profile of one of the tests, from reheating furnace exit to the cooling bed.
For each test, a suitable number of samples was selected for technological and metallurgical characterization. The bend tests and elongation measurements were done using several methods described in various international standards. Figure 8 shows the effects of bend tests on some samples, according to various standards.
The rolling tests in conjunction with metallographic and technological characterization made it possible to deter-



Cooling Time	Temperature	Microstrucutural characteristics for composition 2#	
[s]	[°C]	Sub-surface area	Core
1.0	640	Martensite + PF	Bainite in ferritic pearlitic strufture
2.0	471	Martensite + PF	Bainite and Ferrite
3.0	430	Martensite	Martensite + PF
4.0	277	Martensite + PF	Martensite + PF

PF = Proeutectoid ferrite in trace amounts (<5%)

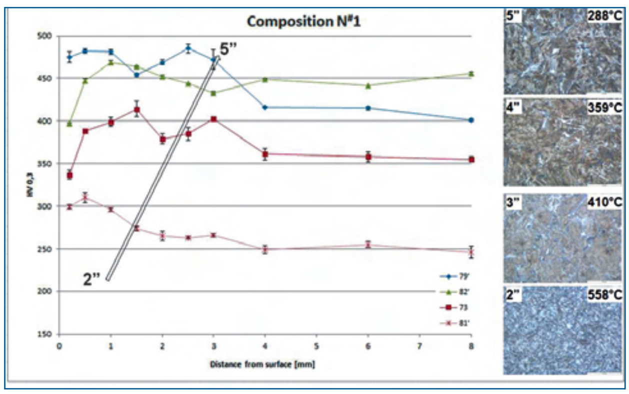
Fig. 4 – Results from microstructural analysis of rebar core with composition #2 and microhardness profiles within the cross-sectional area of the quenched rebar, at increasing cooling times from 1" to 4".



Cooling Time	Temperature	Microstrucutural characteristics for composition 2#	
[s]	[°C]	Sub-surface area	Core
1.0	635	Martensite + PF	Bainite in ferritic pearlitic strufture
2.0	526	Martensite + PF	Bainite
3.0	430	Martensite	Martensite + PF
4.0	313	Martensite + PF	Martensite + PF

PF = Proeutectoid ferrite in trace amounts (<5%)

Fig. 5 – Results from microstructural analysis of rebar core with composition #3 and microhardness profiles within the cross-sectional area of quenched rebar, at increasing cooling times from 1" to 4".



Cooling Time	Temperature	Microstrucutural characteristics for composition 2#	
[s]	[°C]	Sub-surface area	Core
2.0	558	Martensite + Bainite	Bainite
3.0	410	Martensite + PF	Martensite + PF
4.0	359	Martensite + FP	Martensite + PF
5.0	288	Martensite + PF	Martensite + PF

PF = Proeutectoid ferrite in trace amounts (<5%)

Fig. 6 – Results from microstructural analysis of rebar core with composition #1 and microhardness profiles within the cross-sectional area of the quenched rebar, at increasing cooling times from 1" to 5".

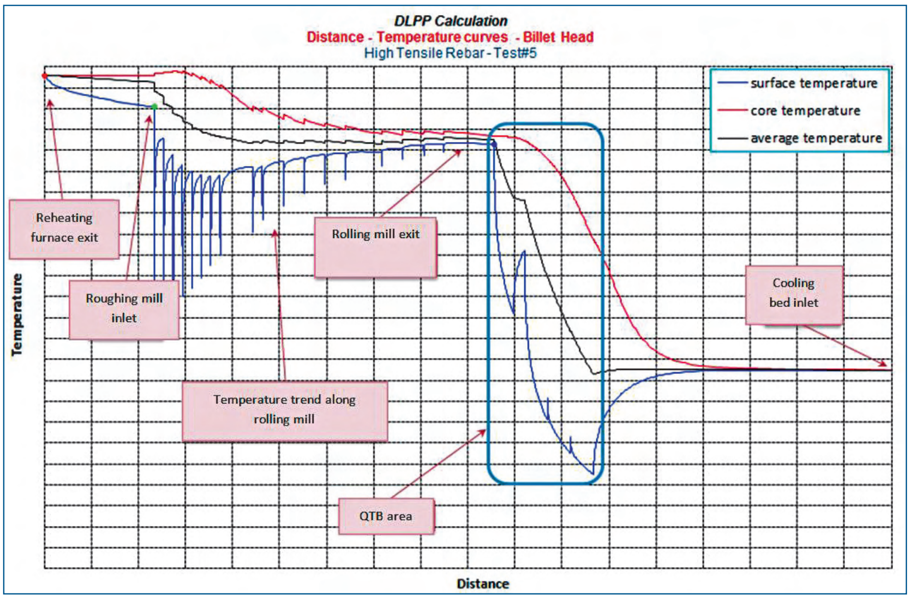


Fig. 7 – Thermal simulation using DLPP: temperature trend of the bar from reheating furnace exit to cooling bed entry.

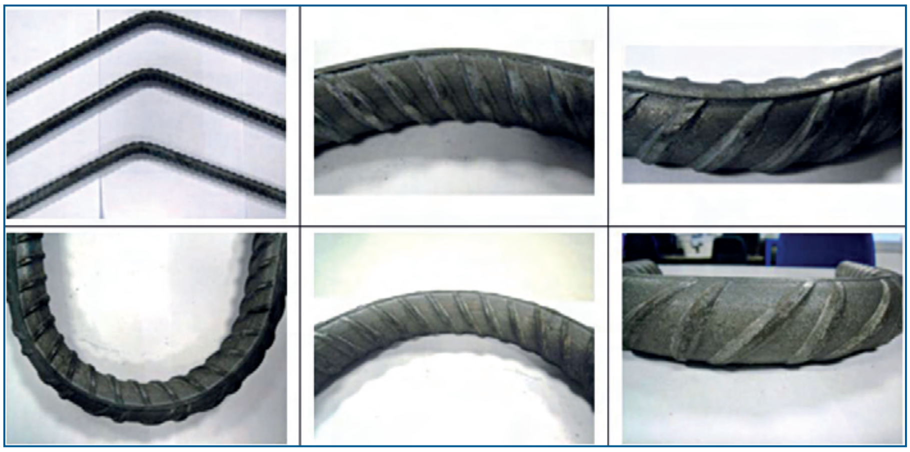


Fig. 8 – Bend tests done on samples of high-tensile rebar heat-treated in line.

mine the limitations of the QTB process in the production of high yield strength rebar, in terms of cooling method, operating flow rates/pressures, chemical compositions, productivity and process stability.

It is important to note that for rebars with the same final technological properties, the processing temperatures necessarily differ depending on the composition. In fact, core hardening is necessary in some cases in order to reach the desired figures. This aspect must be taken into consideration to determine the risk of brittle phases being generated, and the possible creation of cracks (enhanced by the quenching process). Figure 9 shows a series of macrographs (hardening depth) and micrographs (surface, core): one of them highlights a crack generated by a defect that spread within the bar.

Just like in the lab tests, the microhardness profiles in various processing conditions were examined. This made it possible to determine the exact hardening depth and the effect of the metallurgical transformations.

CONCLUSIONS

The lab experiments made it possible to assess the behavior of 3 different chemical compositions after subjecting DIA 16mm rebars to hardening and self-tempering.

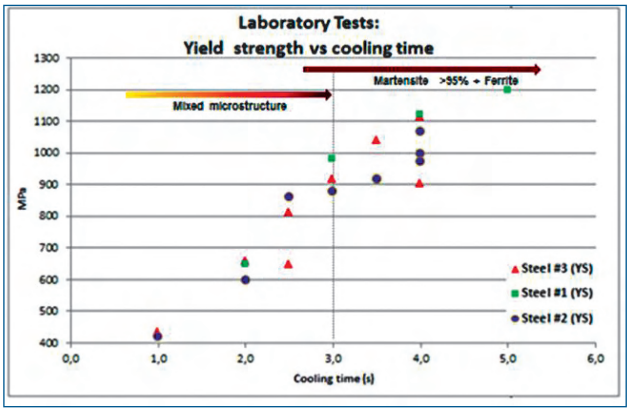


Fig. 10 – Yield strength measured with increasing cooling times of rebar in lab tests.

The industrial-scale tests made it possible to evaluate the performance of the QTB process in the production of high yield strength rebar (greater than 1000MPa) in terms of operating flow rates / pressure, optimized chemical compositions, productivity and process stability.

In some DANIELI plants, the QTB process is already being used for the production of high-strength steels.

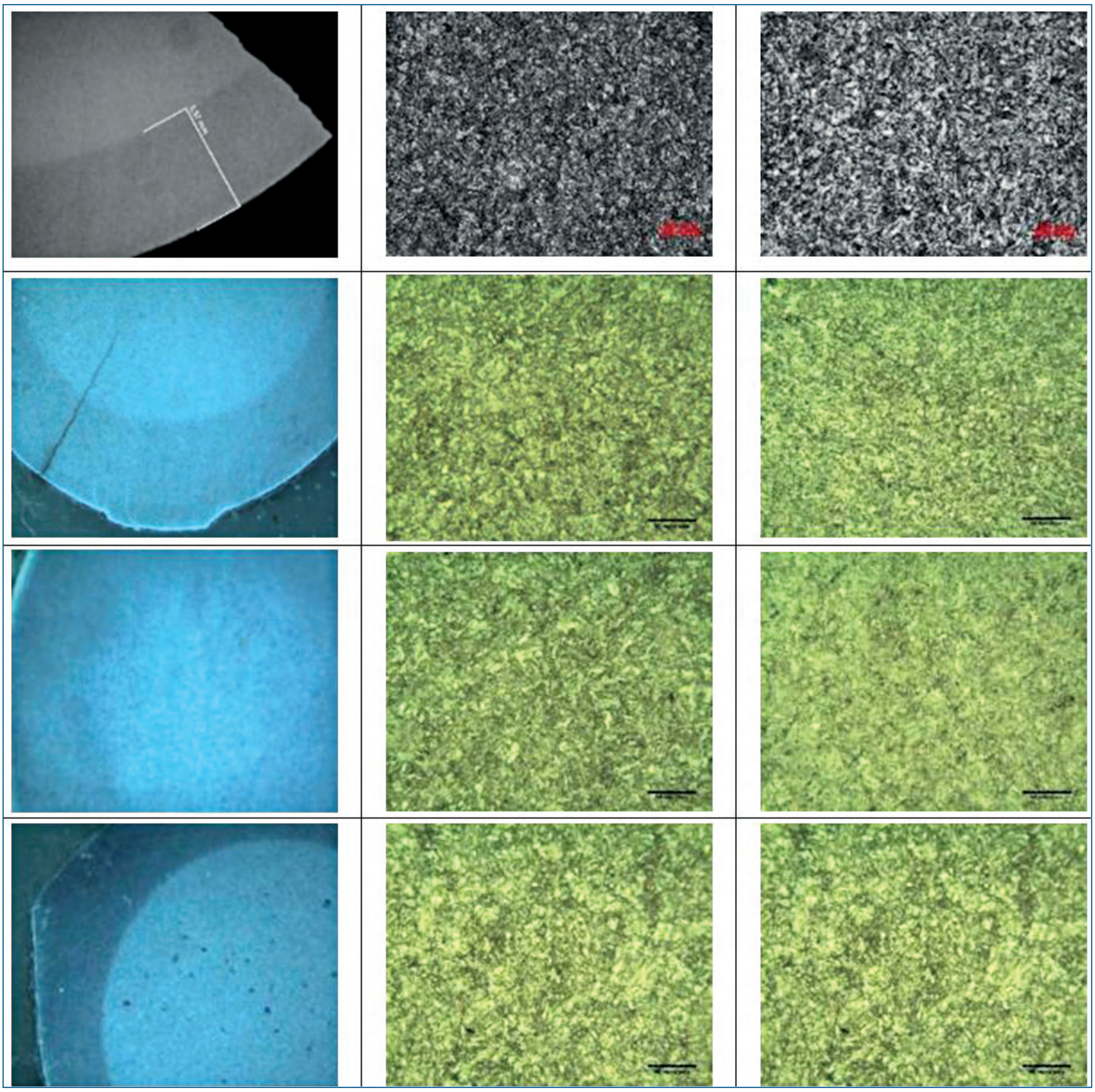


Fig. 9 – Examples of macrographs and micrographs (surface, core) for high yield strength rebar treated with QTB at different processing temperatures. Note the sample with a crack generated by a defect.

BIBLIOGRAPHY

[1] M.MIYAJIMA, The Japanese Experience in Design and Application of Seismic Grade Rebar, Proceedings of Int. Seminar on production and Application of High Strength Seismic Grade Rebar Containing Vanadium, page 12, Beijing 2010

[2] S. MORITA, S. HITOSHI, Development of high strength mild steel deformed bars for high performance reinforced concrete structural members, paper No. 1742. 11th world conference on Earthquake Engineering, ISBN: 0 08 042822 3, Elsevier 1996

[3] WJE Wiss, Janney, Elstner Associates, Inc., Mechanical Properties of ASTM A1035 High Strength Steel Bar Reinforcement, Final Report WJE No. 2008.9901.0, 2008

[4] Y. CAIFU, Development of High Strength Construction Rebars, Proceedings of Int. Seminar on production and Application of High Strength Seismic Grade Rebar Containing Vanadium, page 58, Beijing 2010

[5] J. HUAIZOHONG, Y. CAIFU, Z. YONGQUAN, Strengthening effects of nitrogen on 20MnSi rebar containing vanadium, Special Steel, Vol.21,No.5, page 20, 2000

[6] WENG YUQUING, Ultra fine grain steel, Metallurgical Industry Press, Beijing, 2003

[7] ENGINEERING NEWS RECORD, High strength rebar called revolutionary, Aug/Sept, 2007

[8] C. FABBRO, M. CIMOLINO High Carbon Grades for Wire Rod Lines - The Core of Danieli Technology, AISTech 2014 Iron & Steel Technology, Indianapolis IN, USA, May 2014