HIGH SPEED PRODUCTION OF REINFORCING BAR WITH THE LATEST EQUIPMENT TECHNOLOGY ON ROD AND BAR MILLS [1]

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Abstract
The application of the versatile Siemens VAI water boxes with split design nozzles to the production of quenched and tempered rebar in both coils and straight lengths has been successful in several mills in recent years. This paper describes the operational and metallurgical capabilities of this process (HYQST, for High Yield Quenched and Self-Tempered) as well as the equipment needed. Suited to modern high-speed rod rolling operations as well as bar production lines, the combination of rolling, cooling and ancillary equipment permits the production of high strength, weldable and ductile reinforcing rods without the use of costly micro-alloying additions or subsequent off-line cold deformation processing. This paper describes the system and presents features and results from several recent installations.
Key words: Reinforcing; Rebar; Quenching; Rod; Bar; Rolling; Morgan.

ULTIMAS TECNOLOGIAS PARA PRODUÇÃO EM ALTA VELOCIDADE DE BARRA DE CONTRUÇÃO PARA LAMINADORES DE FIO MAQUINAS E BARRAS

Resumo
A versatilidade na aplicação das caixas de resfriamento da Siemens VAI com o modelo de insertos bi-partido para produção de vergalhão termo-tratado em bobinas e barras tem sido um sucesso nestes últimos anos. Este trabalho descreve as capacidades operacionais e metalúrgicas deste processo que chamamos de HYQST (High Yield Quenched and Self-Tempered – Alta Resistência Temperado e revenido) assim como dos equipamentos utilizados. Desenhado para laminadores modernos de alta velocidade tanto de barras como de fio máquina, a combinação da laminação com o resfriamento e dos equipamentos auxiliares permitem obter aço de alta resistência mecânica, soldáveis e duteis, reduzindo a necessidade de adição de ligas. Este trabalho descrever o sistema e os resultados encontrados em instalações recentes.
Palavras-chave: Vergalhão; Tempera; Bobina; Barra; Laminação; Morgan.

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INTRODUCTION

Ribbed reinforcing products for the construction industry continue to be one of the staples of the long products markets. Demand for this class of products has varied over the years along with cycles in the construction industry, but has generally been increasing in recent years in developing countries and in countries with established infrastructures that need upgrading.[1] In addition, more technical requirements for these products have been developed, particularly for geographical areas subject to earthquake activity.[2] From the processing perspective of the long products manufacturer, the class of reinforcing products most challenging is that of high strength, weldable rebar with little or no alloying needed to achieve mechanical properties. The properties can be obtained through three main processing techniques. The first technique is micro-alloying with Vanadium and/or Niobium in combination with relatively high levels of Manganese. See for example, Hulka and Keisterkamp.[3] This approach enables the physical properties to be tailored to a wide range of specifications, but it can result in property variability through the product. Also, the alloys are expensive and require more careful control of melt shop, caster and reheating practices.

The second technique is off-line cold forming – this can be either cold rolling or drawing followed by cold indenting, or cold stretching of ribbed hot rolled rod.[4] These off-line processes are carried out at significantly lower rates than the rolling operation and require additional investment in manpower and equipment. Also, the resulting properties tend to be restricted in ductility and the product had relatively poor fire resistance.

The third technique is thermo-mechanical processing in the rolling line, consisting of a combination of finish rolling temperatures and controlled cooling to obtain a microstructure and associated mechanical properties in the as-rolled ribbed product. The most popular form of this technique is rapid quenching of the rolled ribbed product.

Several in-line quenching systems have been developed since the 1970s, using various types of water cooling boxes and ancillary equipment, depending on whether the product was coiled rod or straight bar and on the finishing speeds of the respective products.[5,6] The focus of this paper is on one of the most recent of these systems, that of the HYQST (High Yield Quenched and Self-Temper) system that was developed by Morgan.

PRODUCT SPECIFICATIONS

The chemical composition required for HYQST product is a lower carbon equivalent which is weldable, and meets the standard elongation and bend test requirements for many specifications. There are many regional specifications around the world for patterned rebar and the HYQST process can be used to manufacture bars which comply with all of these specifications. This allows manufacturers worldwide many options and opportunities to meet even the most demanding certification requirements for a license to manufacture and certify rebar. It therefore provides the opportunity to export rebar to countries outside the manufacturing country.

The HYQST process is currently producing rod and bar to that meet the requirements of the international standards listed in Table 1.

Table 1: Basic summary of international steel reinforcement standards

Country	Specification	Grade	Minimum Yield Strength (MPa)	Minimum Tensile Strength (MPa)	TS/YS Ratio	Minimum Elongation (%)
Brazil	NBR 7480	CA – 25	250		1.20	18 (A10)
		CA – 50	500		1.10	8 (A10)
		CA - 60	600		1.05	5 (A10)
China	GB 1499	HRB335	335	490		16
		HRB400	400	570		14
		HRB500	500	630		12
India	IS:1786	FE 415	415	485	1.10	14.5
		FE 500	500	545	1.08	12
		FE 550	550	585	1.06	8
UK	BS 4449	500A	500	1.05		2.5 (Agt)
		500B	500	1.08		5.0 (Agt)
		500C	500		≥1.15, <1.35	7.5 (Agt)
Spain	UNE 36065	B400 SD	400	480	≥1.20, <1.35	9 (Agt) & 20 (A5)
		B500 SD	500	585	≥1.15, <1.35	8 (Agt) & 16 (A5)

Table 2 gives the basic chemical composition required for the HYQST process in order to meet the above specifications.

Table 2 - Chemical composition of rod and bar products for a weldable high strength rebar made using the HYQST process

Grade	C	Mn	V
FE 415 FE 500	0.18-0.23	0.70-1.0	-
FE 550	0.20-0.23	0.85-1.3	-

COOLING PRINCIPLES

High Yield Strength is produced by a combination of fine grain size and a self-tempered martensitic surface zone. The relative contributions to strength from the various hardening processes that are involved in the overall processing system are shown in Figure 1. Clearly, it is the refinement of the grain size that contributes the most to the overall strengthening process.

The rolling conditions that prevail in modern high-speed rolling blocks produce "dynamic recrystallization". This process is strain and temperature dependent such that this initial grain size is inversely proportional to increasing strain and decreasing rolling temperature. The strain is largely fixed by the active pass design, but the furnace re-heat temperature and pre-block cooling can control the temperature. Final rolling temperature should not exceed about 1000℃ whenever possible to avoid excessively long water cooling lengths.

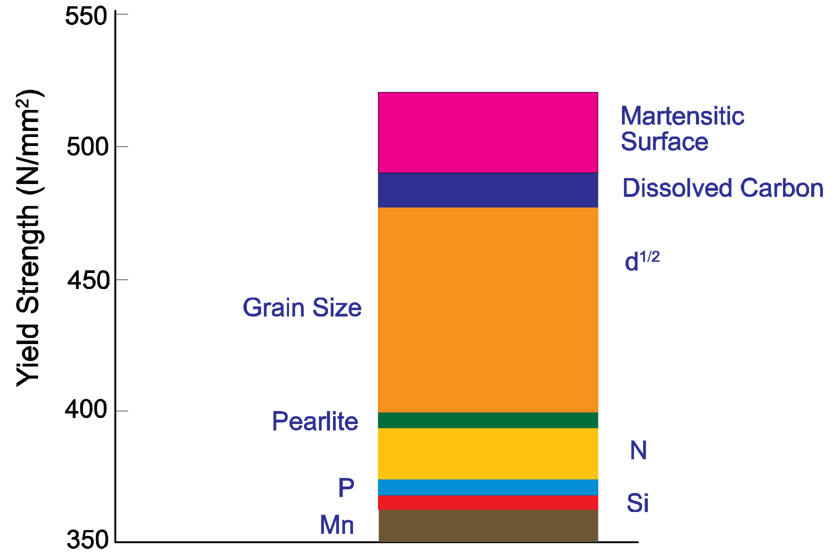

Figure 1 - Strengthening Components in the HYQST Process.(7)

Upon exiting the last rolling stand, the recrystallized grains will grow rapidly, and consequently it is necessary to position the water boxes as close as possible to the last pass in the finishing block, so that immediate cooling of the rod can take place to lock the grain structure.

The HYQST process achieves a very high rate of heat transfer which suppresses the rod surface temperature below that required to form low carbon Martensite. As the stock leaves the water cooling section, the remaining heat in the core dissipates and due to the sharp temperature gradient the surface is rapidly heated and the core lowered in temperature to an equilibrium temperature suitable for tempering. Because cooling is designed to allow the core temperature to fall to a sub critical temperature the surface does not recrystallize. Figure 2 shows the essential metallurgical basis of the process

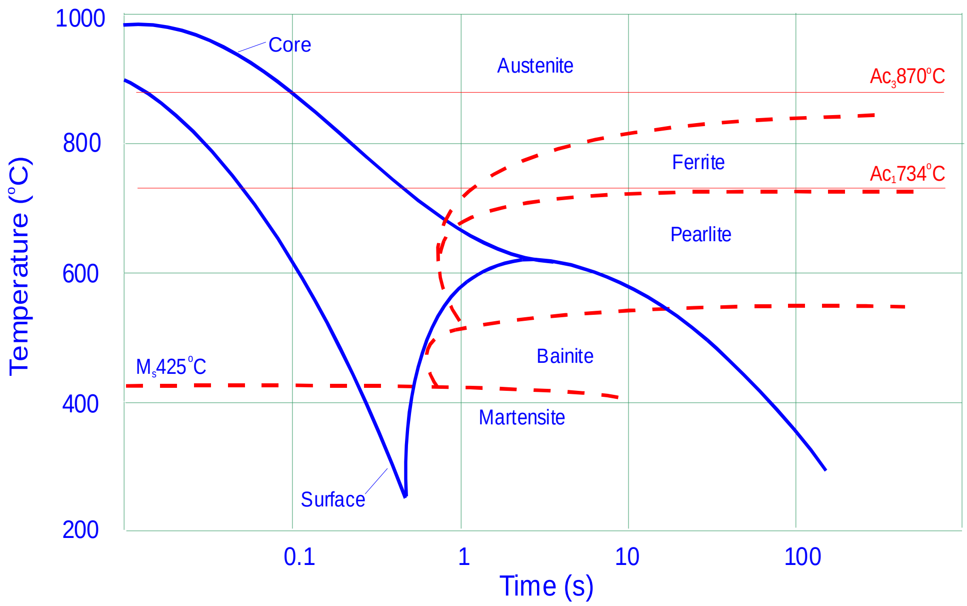

Figure 2 – CCT Diagram superimposed with HYQST Process Line.

Tempering allows the surface to become tough and the core strong. The cross-section is substantially a core with a distinct outer band of tempered martensite. (Figure 3). A macro view of an etched sample may appear to show a thicker layer but this includes a transition zone, but for most samples the martensite layer can only be seen by using a high-powered microscope. The surface may also comprise various fast transformation products but tempered martensite will be the predominate phase running from the surface towards the transition zone. The Austenite at the rod center will have been cooled to a temperature close to the nose of the Pearlite start temperature, ensuring that upon subsequent phase transformation the Ferrite and Pearlite grains produced will be relatively fine in nature, and as such will contribute substantially to the strengthening process.

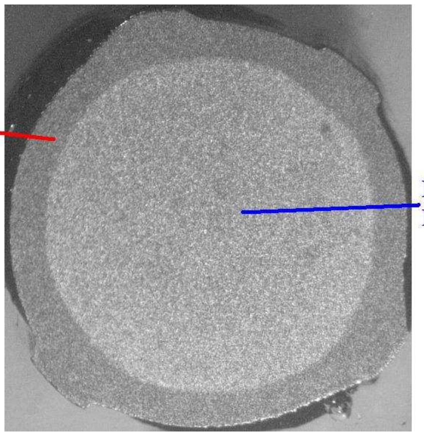

Figure 3 – Etched cross-section macrograph of a typical HYQST structure.

As a general rule, it is necessary to reduce the surface temperature of around 350℃ or less, to a final equalized temperature of between 610oC and 650oC to produce HYQST rods to meet a 500 N/mm^2 standard for Yield Strength. Remnant heat in the process section, coupled with the latent heat released during transformation of the Austenite, will automatically temper the low carbon surface Martensite, making it strong, yet very ductile. Temperature equalization is substantially complete before the rods are laid onto the Stelmor® Conveyor.
Consequently the mechanical properties reflect high strength, moderate to low ductility, but a higher tensile strength to yield strength ratio than hot rolled microalloyed rebar. This ratio is becoming more important in specifications, particularly in earth tremor regions where fracture resistant bars are needed. As the ratio increases, the resistance to fracture increases.
For larger diameter bars vanadium may be added to contribute to the yield strength. In addition, it may increase weld metal toughness and refine the heat affected zone grain structure which means the weld metal retains metal strength at least the same as the bar and more importantly the moderate ductility which allows bending of the bar.

THE HYQST SYSTEM

There are several key components of the HYQST system that enable the efficient production of the quenched and tempered rebar in the rolling mill line. These are the cooling elements for quenching and guiding of the material, pinch rolls for preventing cobbles and controlling the product speed, devices for coiling or guiding to a laying head / cooling bed, plus a control system for insuring processing temperatures. Different combinations are required depending on whether the product is coiled (hereinafter called Rod) or straight (hereinafter called Bar). HYQST in coil form is typically produced in sizes from 6mm to 16mm. In straight lengths to a cooling bed, the product size typically ranges from 8mm or 10mm up to 40mm, but can be as large as 63.5mm.

A key feature of the HYQST system is the cooling nozzles, which are split longitudinally and hinged to allow for opening, thereby exposing the entire inside bore of the assembly. This is very useful for inspection and cleaning. The nozzles are installed and interchanged easily by hand, resting on machined interfaces which insure excellent alignment of all parts within the water box. A clamping mechanism secures the nozzle halves together during production. The latest generation of the split nozzle design features a cooling nozzle used in conjunction with a nozzle extension, which increases the efficiency of the system, so that the water requirements are less than previous generations. Figure 4 shows an example of the nozzle arrangement in the box. For quick changing of nozzle bores, the water boxes are available in a traversing style, such as shown in Figure 5.

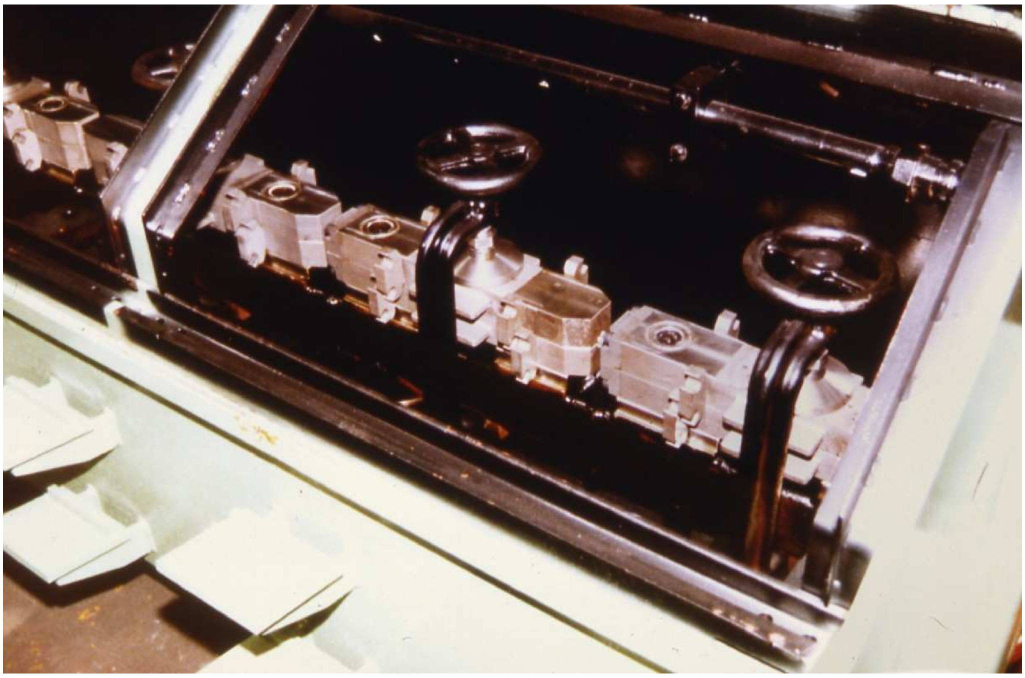

Figure 4 – Nozzle and clamping arrangement in a water box.

Rod Mills – The most critical aspect of HYQST production in a rolling mill is usually maximum speed of small diameter products. The high speeds in a rod mill line are handled with a combination of cooling water application; nozzle bore selection, pinch roll positioning and operation, and laying head design and operation. The water cooling line typically consists of a series of cooling boxes after the No-Twist® Mill, Reducing/Sizing Mill or Mini-finishing Mill. However, one or more cooling boxes may be used ahead of the finishing block to control rolling temperature in the finishing stands.

Figure 5 – Traversing water box system.

The water box cooling length is selected to provide the required quenching time for each size to be rolled, using a combination of cooling nozzles with replaceable inserts and air stripping elements to contain the water in the box. The water boxes are positioned as close as possible to the exit of the rolling mill, in order to initiate the quenching process soon after rolling. The boxes can be designed as either having interchangeable nozzles in a stationary box or as traversing boxes with several cooling paths for rapid change capability.

In the rod mill, one or more intermediate pinch rolls are provided with the water boxes to help give stability to the rod and minimize the amount of un-cooled head end length on the coil. Since it is not possible to pass small diameter rod with water in the nozzles, it is necessary to keep the water off until some portion of the billet is through the cooling line, resulting in an un-cooled head end length that requires subsequent discarding. Figure 6 shows a water box and intermediate pinch roll arrangement.

Another critical piece of equipment for HYQST production in the rod line is the Laying Head, an example of which is shown in Figure 7. As a result of the quenching operation, the rod is relatively stiff. While this does not significantly impede the formation of rings in the laying head, it does make it more difficult for the formed rings to fall down and form a good package on the Stelmor® conveyor. Therefore, it is necessary to have a larger angle of inclination on the laying head to induce the rings to lay properly, particularly on large sizes, i.e., ≥ 10mm. A 20º angle is usually recommended for this application.

Figure 6 - Water box and intermediate pinch roll arrangement.

Figure 7 - Pinch Roll and Laying Head at entry to Stelmor® conveyor.

Bar Mills - For a bar mill rolling to a cooling bed, the water boxes are arranged in a continuous line, with either interchangeable nozzles in a single line box, several paths with different size nozzles to accommodate slit and single line rolling, or traversing with multiple paths for ultimate flexibility and rapid change capability. Figure 8 shows an example of a multiple-line traversing water box system for production of HYQST bars from 8mm to 63mm, including slitting on the smaller sizes.

Figure 8 - Traversing water boxes for slit and single strand rolling.

Temperature Control – Maintaining the required level and uniformity of mechanical and metallurgical properties requires tight control of processing temperatures as well as billet quality. A water box control system has been developed for use in rod mills and bar mills to insure that the desired processing temperatures are achieved and maintained at critical points in the rolling mill line. This system basically consists of a PC with an HMI for the operator interface, links with the mill Level 2 System for product requirements, input from pyrometers for product temperatures, and links to PLCs for control of valves and other mechanical components.

This system, called METCS (Morgan Enhanced Temperature Control System), provides features for setup from stored product cooling codes, automatic on/off sequencing of all valves, closed loop flow and temperature control, plus process variable trending. Through a graphic process interface, the operators and process engineers have the capability to control the system parameters and insure that the desired quality is achieved consistently.

HYQST INSTALLATIONS AND PRODUCTION RESULTS

The HYQST quenching systems are in operation in a variety of rod mills and bar mills, as a result of mill modernization projects or new mill construction. In addition, several new mills in various stages of design, manufacturing or installation also include this technology.

For rod products, HYQST is being produced in sizes from 6mm to 16mm, with many mills concentrating on 8, 10 & 12mm, due to market demands and limits on mill configuration and equipment. One of the most common limitations on mill upgrade projects has been the laying head arrangement, with older mills having very shallow angles that preclude rolling of sizes greater than 10mm or 12mm without special means of forcing the product to lay properly on the cooling conveyor.

For bar products rolled to cooling beds, sizes from 8mm to 63.2mm are being successfully rolled through the HYQST system. On small sizes, production is carried out either through slitting and finish rolling in the finishing train of a conventional bar mill or through slitting after the intermediate mill and taking each line independently through a No-Twist® finishing block and using a high speed cooling bed entry system like the Rotary Entry System (RES) developed at Morgan. In the first case, the water cooling system consists of multiple parallel sets of cooling nozzles in the water boxes, with sufficient length to cool each of the products. The left side of Figure 9 shows an example of a box set up to handle up to 4-slit products. In the second case, which enables finishing at speeds up to 34-38 m/s, the water boxes have a single path, but are significantly longer to enable adequate quenching time for the product. The image on the right of Figure 9 shows an example of the cooling bed with RES system that has been designed for these high speeds.

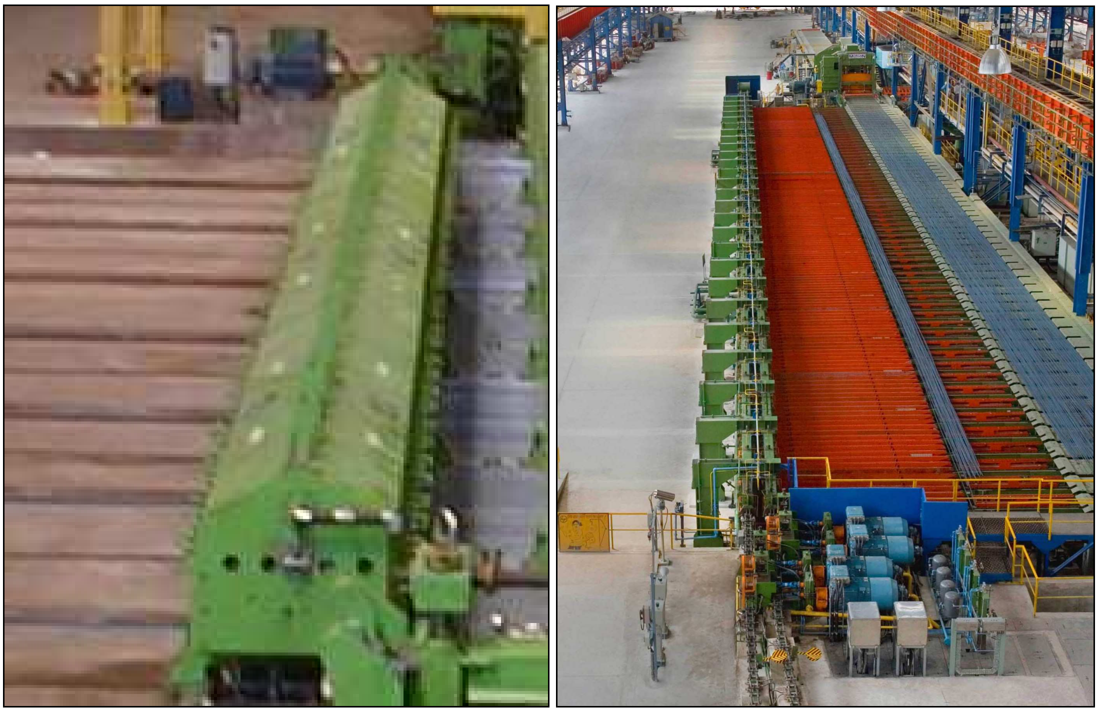

Figure 9 – Water box line with 4 paths for slit rolling (left) and cooling bed with Rotary Entry System for high speed rolling (right).

Table 3 shows some examples of design parameters for production of HYQST in some recent rod and bar rolling mills. Mills currently operating with a HYQST system are located in India, Luxembourg, Morocco, Spain, Poland and the United Kingdom. Additional systems will soon be implemented in Brazil and Dubai, as well as several more locations within India.

As an example of HYQST products from one of the above rod mills, 8.0mm rod was rolled at 64 m/s (approx. 90 tons/hour) on a single strand mill with a No-Twist® mill and water box system with intermediate pinch rolls. Shown in Figure 10 are photographs of cross-sections from a sample taken from the coil after trimming. Grain size of the core is estimated at ASTM 11/12 (5-8 μm). This rod contained no alloying elements (V or Nb) and met the requirements of high strength and ductility grade B500SD to be used in European earthquake regions.

Table 3: Rolling parameters of some current HYQST installations

Mill	Mill Type	Product Size (mm)	Maximum Speed (m/s)	No. of Strands
A	Rod	6.0	85.0	1
		8.0	60.0	1
		10.0	41.0	1
		12.0	29.0	1
		16.0	16.0	1
B	Rod	6.3	85.0	1
		8.0	85.0	1
		10.0	59.4	1
		12.5	38	1
		16.0	23.2	1
C	Bar	8.0	17	4 slit
		10.0	17	4 slit
		12.0	12.5	4 slit
		14.0	12.3	3 slit
		16.0	9.3	2 slit
		18.5		2 slit
		20.0	11.5	2 slit
		25.0	11.5	1
		28.0	9.2	1
		32.0	7	1
		40.0	4.5	1
		50.0	2.9	1
		63.2	1.8	1
D	Bar	8	34	2
		10	36	2
		12	26.4	2
		16	14.9	2
E	Bar	8	34	2
		10	38	2
		12	35	2
		16	19.7	2
		20	25.2	1

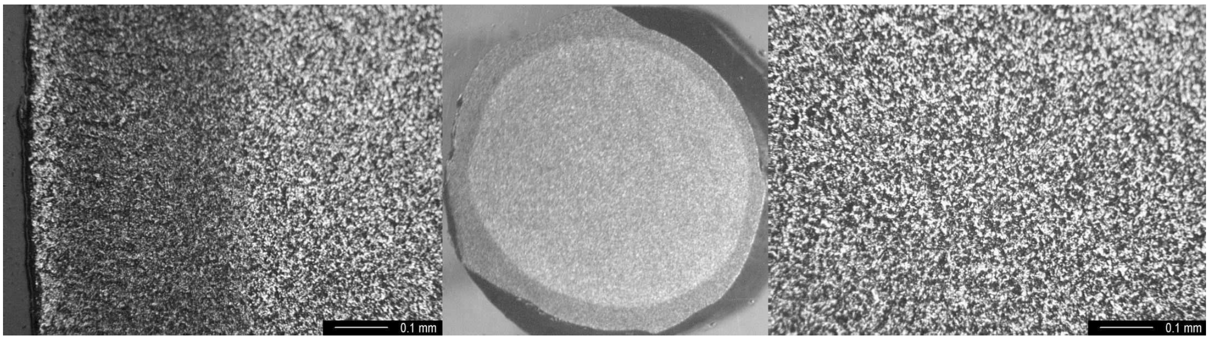

Figure 10 – 8mm HYQST rod showing the etched surface (100x), cross-section macro, and core (100x).

CONCLUSIONS

HYQST (High Yield Quenched and Self-Tempered) system is installed in mills throughout the world with many more installations scheduled in the near future. Coiled rod from 6 to 16mm and straight length bars from 8 to 63.5mm are being produced on modern high-speed rod and bar production lines to meet the most demanding steel reinforcement requirements arouind the globe. The combination of rolling, cooling and ancillary equipment permits the production of high strength, weldable and ductile reinforcing rods without the use of costly micro-alloying additions or subsequent off-line cold deformation processing. At the heart of the process are the versatile water boxes with split design nozzles. pinch rolls, laying heads, Rotary Entry Systems, and process control systems provide the mill operators complete control for repeatable, high speed production of rebar.

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