The Advantage of Hot-Rolling Process without Reheating Furnace on TMT Quality

<u>Alternate Title:</u>

The Green Technology of Steel Rolling:Direct Hot Rolling and Its Quality

Dr. H. M. Mamun Al Rashed and Dr. Kazi Md. Shorowordi

Department of Materials and Metallurgical Engineering
Bangladesh University of Engineering and Technology, Dhaka – 1000

1. Introduction

Steel can adapt to changing of requirements since its structure can be influenced by processing and alloying with different alloying elements. This is why steel is frequently known as the 'gold-standard' against which emerging structural materials are compared. Moreover, this is not a stationary standard; along with its commercial achievement, its impressive yield and efficiency are exclusive, second to none. It is not surprising thus to observe that steel and its technology share a major role in improving quality of life, and it is often accepted as granted. Undoubtedly, this phenomenalcrown of steel is attributed to the variety of microstructures and properties that can be generated by solid-state phase transformation and processing.

Though cold rolling of non-ferrous alloys has been practicing for more than five centuries, the history hot rolling (reduction of thickness—working—at elevated temperature) of steel dates back to latter half of seventeenth century. The industrial revolution in the nineteenth century and continuous growth of demand for bars, rails and structural products motivated the technology and scientific development of steel rolling at elevated temperature. This was garnished with increase of roll speed,modernisation of technology and use of tandem mill. In the mid-nineteen fifty's, development of continuous casting of steel (first test run accomplished in 1947 at *Junghans* of former West Germany) boosted the production efficiency of steel.

In recent days, steel products are used for reinforcement of concrete in buildings, bridges and marine structures, and reinforcement bars (rebar) therefore appear as a competitor to structural steel plates and sections. At one time, rebars were regarded as low-grade, undemanding steel products. However, due to concern for higher-strength steel and the requirement for good chemical and mechanical properties, steel rebars are now made to high quality standards.

2. TMT Process

Hot rolling of steel rebars can be achieved is several ways. For example, rolling can be done above upper cooling transformation temperature, Ar_3. Here, deformation occurs only in the gamma austenite region. In other processes, rolling is interrupted where steel is rolled both in gamma austenite and in gamma austenite/alpha ferrite regions. Also, steel can be rolled with a low finishing temperature rolling, where finishing passes are conducted below the lower cooling transformation temperature, Ar_1, allowing deformation in the alpha ferrite region.In general, temperature at the finishing pass and the amount of deformation affect mechanical properties of rolled steel, and subsequently interest was grown towards controlled rolling where desired finishing temperature can be designed to allow deformation in a particular microstructural phase region. This is characterised as thermo-mechanical treatment (TMT). This is essentially a controlled and simultaneous thermal and deformation treatment involving phase transformation.

The *CRM laboratories*at Liege in Belgium in the mid-1970s reported about an in-line heat treatment process which facilitated high-strength properties of rebars. This process was designated as*Tempcore*process.Rolling followed by controlled coolingallows formation of an outer layer of martensite on the surface of rolled product. This martensite is tempered by conduction of heat from the core of the bars. As a consequence, weldable and high-strength ribbed rebarcan be produced at an affordable cost. This saving is achieved by eliminating the costs associated with cold twisting or micro-alloy additions. This process appears to be very successful, and has been being used throughout the world.

In this process, after passing through the last finishing stand, the rolled bar travels through a designated water cooling station which rapidly cools the outer surface of the bar so that martensitecan form by quenching. In response to this quenching treatment, the bar has an austenite core surrounded by a mixture of austenite and martensite(higher amount of martensite towards surface). After passing through this cooling chamber, the bar is exposed to the atmosphere and the temperature gradient between the core and quenched surface begins to equalise. This leads to self-tempering of the martensitic rim, producing a significant increase in yield strength and ultimate tensile strength, while maintaining adequate ductility. During this second stage, untransformed austenite in the outer layer of bar may transform to bainite. The core still remains austenite. The final stage takes place as the bar lies on the cooling bed. This allows transformation of austenitic core. Depending upon factors such as composition, finishing temperature and cooling rate, the core can transform to ferrite and pearlite, or to a mixed microstructure which includes some bainite. Thus, the Tempcore process produces a variety of microstructures throughout the cross-section, ranging from tempered martensite in the outer layer (rim) to a region which is essentially ferrite and pearlite in the core, with an intermediate zone which may be predominantly bainitic.

There is another TMT process, known as *Thermex*, patented by *Hennigsdorfer Stahl Engg. (HSE) Gmbh*, Germany. After rolling, surface temperature is brought down drastically by intensive and uniform water cooling. The temperature of the core remains largely unaffected. Consequently, the outer shell transforms into martensite, and then annealed by the heat available at the core. The rim and core temperature difference finally equalises, and the resultant bar structure consists of tempered martensite in the outer shell and fine-grained ferrite-pearlite in the core.

3. The Use of Reheating Furnace

Traditionally billets are cast in a continuous casting machine (*CCM*) and are stored in inventory. Then billetsare transferred to the reheating furnace andsubsequently rolled through a series of rolling stands for final desired size and shape.There are a few reasons for using reheating furnaces in rolling plants including obtaining a homogeneous microstructure; softening of steel for subsequent rolling; acquiring a desired initial temperature and dissolving any carbides and nitrides present. During this reheating process, steel microstructure transforms into austenitic structure and grains become of size close to 0.1-1.0 mm. If any small grains were present, they would definitely be consumed by continuous static grain growth.

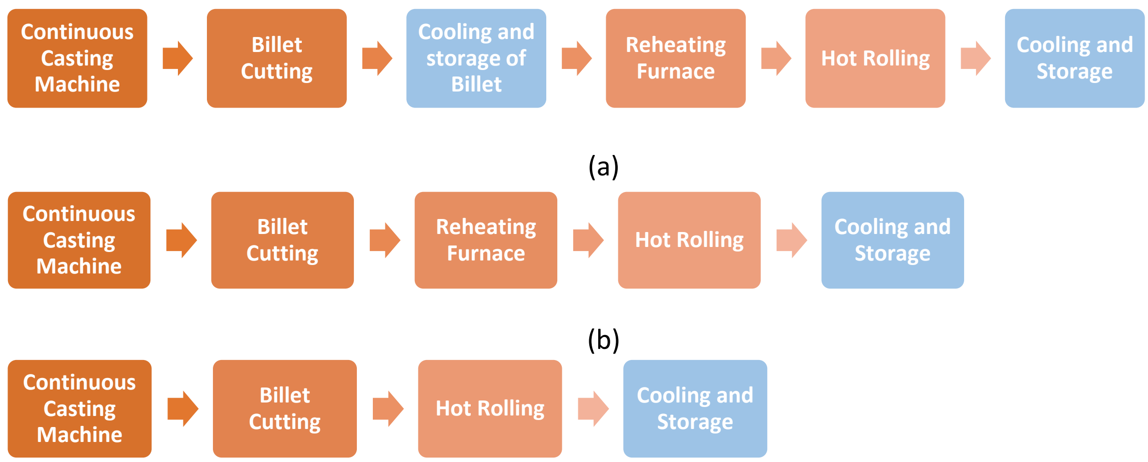
Reheating furnaces may encounter a few problems including non-uniform increase in temperature of the billet due to unjustified travel speed in the reheating furnace which produces a temperature gradient across the billet cross-section; uneven heating; larger surface to volume ratio near the edges compared to centre and heat sink to the supportive members of the billet resulting in skid marks. Moreover, in energy-deprived countries like Bangladesh, where the use of gaseous fossil fuel is limited, gas-fired reheating furnaces cannot always be allowed to consume a large amount of fuel required for proper distribution of heat throughout the cross-section of billets for a prolonged period of time.

A solution to the above-mentioned problems can charging billets from CCMdirectly to the reheating furnace prior to rolling,bypassing billet storage at ambient temperature.More ambitiously, another solution can be sending billets from CCM directly to rolling mill,bypassing reheating furnace and billet inventory.

As outlined above, there can therefore be threeapproaches for hot rolling of rebar: (i) hot billets from CCM are stored separately and thenmoved for heating in reheating furnace prior to rolling; (ii) placing hot billets from CCM into a reheating furnace and raise the temperature before transferring them to the rolling unit, and (iii) transferring hot billets from CCM directly to the rolling unit.

In Method (i), the hot billets are cooled to room temperature and kept in store, and checked for scratches and defective locations; they are then repaired before being heated in the reheating furnace prior to rolling. This is conventional rolling (**CR**) process. In Method (ii), the hot billets are directly transferred, via reheating furnace, to the rolling unit without the cooling process mentioned for Method (i). This is termed as ‘Hot Charging’ or ‘Hot Charge Rolling’(**HCR**) process. In Method (iii), the hot billets are directly transferred to the rolling unit by means of high speed roller table. This is termed as ‘Direct Rolling’ or ‘Direct Hot Rolling’(**DHR**) process. This route is an advanced and upgradedpractice of the former processes. This system has been instigated by modernising rolling technology, practices of heat control and casting techniques. These modificationsassure that heat of billets in CCM are not substantially reduced. In *HCR* route, the billet is guided to reheating furnace before the billet cools off below 650 ^{o}C, reducing the time in reheating furnace. Conversely, in *DHR* route, the cast billet is sent directly to rolling mill, having a precise temperature as per quenching by TMT rebar schedule. The latter method was reportedly first used in Nippon Steel’s Sakai Works in 1981 for slabs.

Fig. 1 shows the hot rolling approaches for rebars. As can be seen, *DHR* process offers quick and shortest path. Fig. 2 shows schematic temperature distribution during the processes mentioned above during casting and hot rolling.



(c)

*Figure 1Different approaches of hot rolling of deformed bars: (a) Conventional Rolling (**CR**); (b) Hot Charge Rolling (**HCR**) and (c) Direct Hot Rolling (**DHR**). Only major sections and units are outlined here. The actual plant or minimill consists of more production units.*

However, there are several issues should be addressed. Use of *HCR* and *DHR* processes instantly raised disputes about (a) physical space where the continuous casting and rolling plants were to be installed and (b) the civil-framework between these units. Many existing integrated steelmaking plants are installed on the assumption that heating of cooled billets are to be performed in the reheating furnace prior to rolling. Important technological parameters for steel millsinclude mill type and configuration and proximity ofthe casting machine to furnace and rolling mill (time required for the transfer of the stock from thesteel plant to the reheating furnace). Therefore, any changes in plant outline may require a major investment on infrastructure. Accordingly, *HCR* and *DHR*may not be realistic for existing plants in terms ofplant layout and operationallogistics. However, new plants with modern layout and advanced concept can opt to any method.

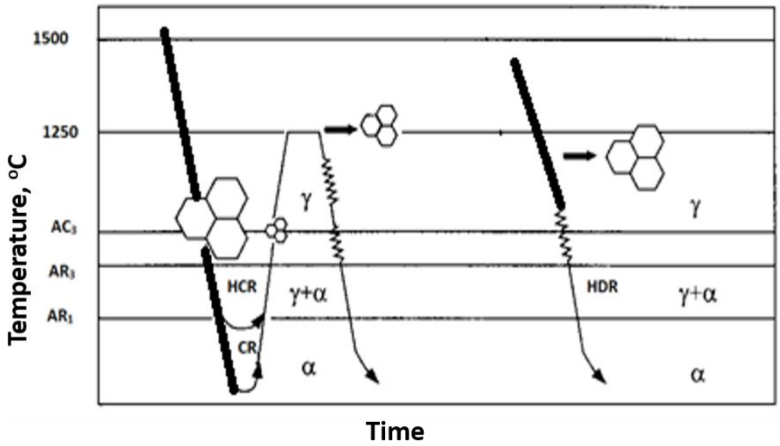


Figure 2A schematic plot of temperature evolution during CR, HCR and DHR processes

4. Direct HotRolling (DHR)

*DHR*technology is one of the advanced production management technologies in steel sector, which representsawareness of green and energy-saving ideology. Contrary to the conventional process of storage and cooling of the billet, the sensible heat from the continuous-cast billets is utilised by charging them directly into the rolling unit.

In *DHR*, the melt, tapped at approximately 1660-1670^{o}C, is transferred to the continuous casting machine quickly without any significant heat loss and is poured into mould at around 1590 ^{o}C. The melt is solidified and cooled down to a temperature of 1050 to 1100 ^{o}Cby PLC controlled indirect demineralised water cooling and secondary direct spray cooling. The solidifying billet is cut immediately and is passed to the rolling mill, ensuring a minimal heat loss.

In*CR* and *HCR* routes, mill-scales are formed in the reheating furnace. Prior to rolling, adherent scale must be removed, in order to avoid a contamination of the stock surface by scale impressed by the rolls (so-called 'rolled in matter'). This scale represents around 2% of material lost. Since reheating furnace step is not required in *DHR* process, such loss will not occur. In Nakayama Steel Products Co. Ltd., Osaka, Japan, introduction of *DHR* resulted 0.74% improvement of yield in terms of surface scale. Furthermore, there would not be any penetration of nitrate and phosphate into billet as suspected to occur during reheating if circulating air/oxygen is not controlled properly.Decrease in scale loss and decarburisation depth also result from higher charging temperature. Therefore, effective utilisation of hot billet improves yields and product quality due to reduced scaling and decarburisation.

In steel industries, it may be difficult to introduce *DHR* as discussed earlier. A synchronisation among all units and personnel from each section is vital. Achievement will be tainted unless each process involved meets the requirements of doing the required action at the required time without delay. For this reason, *DHR* process needs integrated manufacturing capabilities.A very good process management, quality management and system for coordination of man and machines are mandatory. The crucialprerequisitescomprise of a) continuous production of billets; b) control of billet temperature after it exists caster; c) time billet enters the rolling section; d) defect-free billet charging and a very good clearance rate; e)trouble-free rolling mill and f)good coordination amongst people involved. Quality in *DHR* method depends,in a large fraction, on how they are applicable and achievable on the continuous casting plant including educated personnel on casting floors and availability of semi-product quality prediction system on the plant.

Global awareness for environment requires greater rationalisation of energy use by industries.Steel industries worldwide with production of 1129 Mt in 2005 emitted 2,200 to 2,500MtCO_2 or about 6% to 7% of global anthropogenic emissions. Hot charging in the rolling plant, buffer soaking pit, hot tunnel,Direct Hot charging to the rolling plant, etc. are the outcome of the challenges to reduce energy consumption.Thetemperature optimisation during rolling process by hot charging to the rolling plant can reduce energy andenvironment losses. This can thus be considered a green technology.

Energy saving is the key benefit as ambient cooling and subsequent reheating of billet is avoided in *DHR*.For example, it was reported that in *CR* process, the fuel consumption rate is approximately 70,000 kcal/t-steel.Compared to this, in *HCR*, the fuel consumption rate is approximately 20,000 kcal/t-steel, with energy of 50,000kcal/t-steel saved. On the other hand, in *DHR*, no reheating furnace is required, and thus, power saving can be achieved by approximately 70,000 kcal/t steel.Similarly, a German minimill BSW of Badische Group charges billet to reheating furnace at around 750 ^{o}C and achieves 85% of all billets hot charged. This leads to a 50% decrease in natural gas consumption and improved productivity by 11% for sections over 7.5 mm diameter and 55% for 14 mm diameter sections.

Other benefits include low capital investment for main plant, low operational cost of rolled steel, low inventory requirements, reduced manpower, lower civil works, better mill operation and lower yield time with higher yielding efficiency.Interesting to note that in Raipur, India, a steel re-rolling plant used furnace oil for reheating purposes. After implementing *DHR*, fuel saved per tonne of production was 45.34 L/tonne. The investment for civil-work and related service for*DHR* returned in 3 months.

To summarise, the main features and advantages of *DHR* technique include, but not limited to,energy saving, decreasing billet inventory space, reducing production cycle time,maintenance of billet surface quality by prevention of defect resulted during cooling, reduction in overall SO_2, CO and CO_2 emissions,reduction of surface scale (hot billet surface iron oxide), improvement of product yield andultimately achieving a upshot onnatural resource-saving.

5. TMT Responses

For *DHR*technique, it is expected that there will be some changes in thermo-mechanical treatment as billet temperaturehistory is different from *CR* and *HCR*processes. The most noteworthy change is the initial austenite grain size at the roughing mill, which is apparently larger than that obtained after cooling and reheating of billets. This may changemechanical properties of rebars because billets are subjected to heat cycles different from those of conventional reheating processes.The larger the austenite grain size, the larger the ferrite grain size of the final product.Therefore, a modified rolling schedule is compulsory for *DHR*.

Billet from CCM needs to be cooled to the temperature required for solidification before entering the rolling mill with roller conveyor system with canopy arrangements to reduce losses during transferring the billet from caster to roughing stand. In contrast, temperature after the finishing stand must be adequately high so that during TMT approach of cooling the deformed bar remains in the austenite zone. Therefore, temperature profile during the whole process us of utmost importance in *DHR*. Microstructure of billet contains chilled grains, columnar grains and equiaxed grains. During reheating, the grains become entirely equiaxed and austenitic. Since in *DHR* route, billet is directly hot charged, the microstructure still consists of all these three types of grains. During initial rolling passes, these grains must be successfully transformed into equiaxed structure for quality production.

The oscillation, cooling and pausing is done in such a controlled condition through the mould that the liquid steel solidifies into a clean billet. The surface of billet is generally flawless with no scabs and laps. TMT Rebars produced from continuous casting billets generally show high tensile strength and elongation, and there is remarkable consistency of properties.

The martensitic periphery (rim) and soft core improves bendability of TMT rebars. The rebar can be bent around smaller mandrels. This has obvious advantages at construction sites. Besides, in TMT rebars, there are no torsional residual stresses compared to cold twisted bars which imparts good corrosion resistance characteristics. The absence of any cold-worked structural zone and the specific design of steel chemistry in the form of tempered martensite rim on rebar surface provide high thermal resistance to rebars. It is claimed that TMT rebars with modified chemical composition can act as fire resistant steel (FRS) even at elevated temperatures up to 600 ^{o}C. Fire resistance properties for TMT rebars can be obtained by addition of small amounts of chromium and molybdenum.

TMT rebars must have uniform periphery (rim) of martensite. If it is over-quenched, loss of ductility would occur due to thicker rim of martensite. Also, non-uniform periphery due to incorrect mill operation or improper quenching, or eccentric periphery would result in variation of mechanical properties across the rebar.In addition to tensile testing for conformation of mechanical properties, the TMT rebars should be randomly macro-etched, and periphery and core must be examined.

In Fig. 3(a), the uniform and concentric martensite periphery and the soft core are shown. Such rebars will have desired tensile strengths coupled with high elongation. In Fig. 3(b), non-uniform hard periphery signifies that the quenching was not uniform. Such rebars are produced due to incorrect operation by mill personnel. Such bars should be used only after extensive testing. Fig. 3(c) shows a rebar produced by a bad quenching and tempering system. The quenching is suspected to be non-uniform and the test results would definitely not meet standard. Such rebars are typically produced by in-house TMT technology developed by mills. Such bars should never be used in civil construction as properties will vary from bar to bar. In Fig. 4, a micrograph of an 8 mm diameter TMT rebar is shown. The differences in rim thickness can be seen easily. Obviously, remarkable mechanical properties would not be achieved. Therefore, all TMT rebars do not guarantee what the name claims.

Figure 3 Macrographs of TMT rebars having different thicknesses of martensite rim

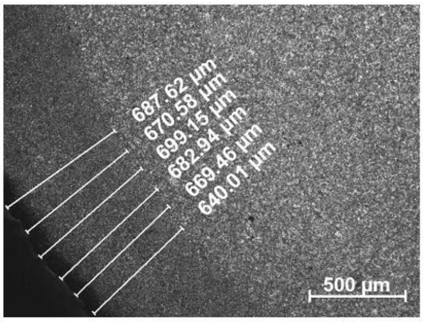


Figure 4Micrograph showing martensite rim thickness in TMT rebar of 8 mm diameter

There is a growing concern regarding the excessive use of the term TMT. It is essential to ensure proper heat treatment for claiming this TMT branding. Otherwise, sub-standard TMT rebars would not only have inferior properties but also possess a risk of disaster while used as structural component. The basic requirements and trend of rebars nowadays is low-cost rebars with guaranteed yield strength of approximately 500 MPa (72.50ksi) with adequate ductility for the seismic (earthquake prone) zones. It should borne in mind that there should be a cap on maximum yield strength for earthquake resistant rebars. Assigning maximum yield strength is necessary to obtain reliability for provisions based on relative strength, such as strong column weak-beam provisions or provisions that compare shear limited by flexural strength to the design shear strength.

A strict control on yield strength value of rebars is essential as it determines the strength of structural member. In controlled TMT rebars, yield strength can be maintained within a close range by careful selection of heat treatment and chemical composition. If yield strength is lower than the specified value, as observed in the case of non-standard TMT rebars, the yield strength will be lower than the expected design value, and thus reducing the margin of safety and increasing risk of premature failure. Since *DHR* is expected to be a total solution package with automation, uniform property is expected by development ofexpected microstructure.

Reinforcement with a higher value of the ratio of tensile strength to yield strength (such as 1.25 for ASTM A706 reinforcement) is expected to spread plasticity in regions of yielding better than reinforcement with a smaller value of this ratio (such as 1.10 for SAS 670 reinforcement). The increased spread of plasticity results in longer plastic hinge lengths and, potentially, increased ductility. Another benefit of having a higher value for this ratio is maintaining or increasing the strength of a member after concrete cover spalling, which results in reduced section depth.Since strength and ductility related capacities in reinforced concrete (*RC)* flexural members are largely controlled by steel rebars, it places certain special requirements on their properties, especially those controlling the inelastic portion of the stress-strain curve which largely depends on the method of rebar manufacturing besides metallurgical/chemical compositions of the steel used. Therefore, exceptional level of quality control is important for any desired TMT approach.

Bangladesh and the north eastern Indian states have long been one of the seismically active regions of the world, and have experienced numerous large earthquakes over centuries. Therefore, building of earthquake-resistant infrastructure warrant special attention. The need to provide concrete reinforcement with ductility appropriate to earthquake-resistant concrete structures, coupled with recent investigations into the structural consequences of the relatively low ductility of cold-worked reinforcement, has led to the introduction of three ductility classes in Australia and New Zealand standards. These are distinguished in requirements by the letters 'L' (low), 'N' (normal) and 'E' (earthquake), placed immediately after the strength-grade number, corresponding with different minimum values for uniform elongation and maximum stress to yield stress ratio. This is adopted in Australian/New Zealand Standard AS/NZS 4671:2001 (Amendment No. 1). An example of such grade is AS/NZS Grade 500E (yield strength: 500 MPa minimum and 600 MPamaximum; Tensile strength-to-yield strength ratio: 1.15-1.40), which is used as reinforcement for members resisting earthquakeeffects in New Zealand. This rebar is produced by either micro-alloying or*quenching and tempering* method. Therefore, TMT rebars can ultimately provide a safe home for all—becoming a commodity—only if it is controlled and quality check is assured.

Along with TMT branding, another term—high-strength reinforcement—is becoming popular worldwide. High-strength reinforcement is defined as reinforcement with a yield strength of 500 MPa(72.50 ksi) or greater. If high strength reinforcement is considered as the primary reinforcement for beams and columns resisting flexure in a special moment frame and for walls resisting flexure and shear, a question on ductility for resisting earthquake effects arises. Use of high-strength reinforcement can result in cost reductions and improved constructability. Benefits include reduced reinforcement quantity, reduced reinforcement congestion, improved placement of concrete, and accelerated reduced construction schedule.

At present, most quality report of TMT rebars contain only elongation to failure values. As the concern for earthquake resistant steel is growing in Bangladesh, u*niform elongation* (ISO Standard 15630:2010) should be reported for TMT rebars. Uniform elongation is the strain that occurs as the rebar reaches its peak stress (tensile strength), expressed as a percentage. This must not be confused with commonly used term 'elongation on failure'. The AS/NZS 4671:2001 requires quoting the uniform elongation. For AS/NZS Grade 500E, *which can be produced by TMT route*, minimum uniform elongation is 10%.Although ASTM A370 and ASTM reinforcement specifications do not require reporting uniform elongation till now, it is a useful property for seismic design because it is more closely related to the maximum elongation (the useable elongation) that should be relied upon in a location of yielding, i.e., a plastic hinge region. According to a report prepared by NIST, March 2014, under National Earthquake Hazards Reduction Program (NEHRP) of U.S. Department of Commerce, useable elongation should be taken as 75% or less of the uniform elongation, because under cyclic loading conditions, steel bars may achieve the equivalent damage state associated with uniform elongation at a smaller elongation. One remarkable improvement in TMT rebar is that they are more ductile, and thus have better capability to withstand dynamic loading as their elongation is expected to be better at higher strengths. In *DHR*, production of clean billet is ensured and any scale loss or probable penetration in minimised; beckoning a strong-yet-ductile rebar. Therefore, it is not surprising if these special *DHR* TMT rebars hold a large stake in the market in near future.

6. DHRChallenges

The strict control of temperature profile from melting to finished product is essential to ensure quality for TMT rebar produced in *DHR*. Therefore, synchronisation of each processing steps to minimise heat loss from the billet is a big challenge. There cannot be any compromise about proper selection of raw materials, selection of acidic/neutral ramming mass, scheduled relining and continuous and automated rolling and cooling system. Rolling mills must ensure available of these facilities for optimisation of heat time.

If there is too much temperature differencesfrom surface to core, the billet may even split during rolling. It is imperativeto prevent surface and internal defects on billets which are detrimental for *DHR*. In fact, successful operation of *DHR* depends largely on the modification of casting speed, optimisation of secondary cooling, installation of insulation hoods and adopting high speed transport after cutting, to preserve heat in the billets and reduce temperature differential between surface and core.Tangshan Iron and Steel Company of Hebei Iron and Steel Group, Tangshan, Hebei, China, reported in 2014 that the hot charging temperature of billet increased by 51.6 °C more than that under air cooling conditions by covering the roller conveyer, and the temperature gradient in the cross-section of the billet reduced by 120 °C. Therefore, insulating covers is suggested for maintaining consistency of temperature distribution across the billet.

Scheduled maintenance for all the facilities is required in time with prior approval from all units for increasing yield/output.

It is important to obtain a defect-free clean hot billet for harmonising the process, along with billet insulation, flow control in mould, etc. Since the scale loss is reduced considerably, it is also necessary to minimise sub-surface defects. This can be met by optimising secondary refining to obtain clean steel, restriction on air oxidation between tundish and mould, improving mould level control and better mould powder properties.Therefore, surface quality must be maintained at satisfactory level so that cooling and scarfing is not required.

Any discrepancies between steel plant and rolling mill performances may hamper production, and force cooling and store of billets. System failure in steel plant or rolling mill, fluctuations in tap-to-tap time (casting time) and staggered maintenance would also lead to a lower yield. Such risks can be curtailed by better management. Commonly known term ‘island view’ between the personnel in the steel plant and rolling plant must be reduced. The manufacturing programme of the steel making plant and the hot rolling mill should be adequately tuned for *DHR* process.

A hot buffer is suggested to eliminate effects of short stoppages in rolling mill, to balance the difference in production speed when rolling.

7. Conclusion

Direct Hot rolling (*DHR*) from billet caster is a new concept in Bangladesh. For existing plants, it would require comprehensive modification of plant layout and expert production management team. Comparative study onDHR TMT rebar with locally produced TMT rebar is suggested in local universities. Due to constraintimposed on fuel consumption, to obtain quality product with uniform property, hot charging of TMT ribbed bars is expected to become popular in Bangladesh as a green technology.

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