Proceedings of the 35th International Conference on Ocean, Offshore and Arctic Engineering
ASME2016OMAE
June 20-24, 2016, Busan, South Korea

OMAE2016-54177

NIOBIUM-BEARING OFFSHORE PLATE STEEL PROCESS METALLURGY, DESIGN AND QUALITY

Steven G. Jansto, Ph.D., MBA
CBMM North America, Inc.
Bridgeville, PA, USA

ABSTRACT

Offshore structural steel design and material requirements continue to present increasing challenges for the steelmaker and fabricators. Niobium-bearing steels currently play a key role in meeting these objectives through the Nb-grain refinement mechanism of the microstructure and cost effective steelmaking. These steels possess a combination of exceptional properties with high strength, excellent weldability, high toughness at low temperature, good ductility, excellent corrosion resistance, and high formability. Reduced variation of Charpy toughness through the thickness of heavy plates is imperative in these offshore platforms to enhance reliability and performance. Toughness variation can be reduced through the proper continuous casting and hot rolling mechanical metallurgy process. These high-performance steels (HPS) possess an optimized balance of these properties to provide maximum cost effective performance in offshore structures at strength levels from 355 to 700MPa with excellent corrosion resistance. This combination of good strength-toughness balance, excellent weathering properties and reduced preheat temperatures for welding in these low carbon Nb-structural steels result in significant cost savings. These enhancements provide structural engineers the opportunity to further improve the structural design and offshore platform performance. Lower carbon Nb-alloy designs have exhibited reduced operational production cost at the steel mill as well, thereby embracing the value-added attribute Nb provides to benefit both the producer and the end user throughout the supply chain.

INTRODUCTION

Offshore platforms and structures have many uses including oil exploration and production, navigation, ship loading and unloading, windtowers and support structures for bridges and causeways. Offshore structures are one of the most visible of these in numerous deep water applications and represent a significant challenge to the design and material engineer. Offshore platforms are huge steel or concrete structures. Offshore structures are designed for installation in the open sea, lakes, and gulfs, many kilometers from shorelines. These structures may be made of steel, reinforced concrete or a combination of both. The offshore oil and gas platforms are generally made of various grades of steel, from mild steel to microalloyed high-strength steel, although some of the older structures were made of reinforced concrete. Within the category of steel platforms, there are various types of structures,

Dependent upon the application and water depth in which they operate, offshore platforms are very heavy and are among the tallest manmade structures on the earth. These offshore structures must function safely for design lifetimes of twenty-five years or more and are subjected to very harsh marine environments at both low and high temperature climates, corrosion challenges, high stresses, fatigue and wave motion impact conditions. Some important design considerations involve the peak loads created by hurricane winds and waves, fatigue loads generated by waves over the platform lifetime and the motion of the platform and/or structure. These platforms are subjected at times to strong currents which create loads on the mooring system. Consequently, fatigue, fracture toughness, stress corrosion resistance and impact toughness behavior are critical mechanical properties for the structural members and platforms. The metallurgical influence of the grain size, uniformity of grain size through the plate thickness, optimal microstructure, steel cleanliness, low residual elemental contents, texture and overall consistency from heat-to-heat are required to meet these challenging offshore low temperature toughness, fatigue and strength applications.

IMPLICATIONS OF LOW CARBON APPROACH

The adoption of the low carbon approach reduces internal operational cost of steel production in the melting, casting and hot rolling operation. It is universally accepted that the lower carbon grades are less prone to surface and internal quality problems. Therefore, from an operational cost perspective, in today's very competitive market environment, there exists a huge opportunity for structural offshore plate mills to improve their profitability by thoroughly assessing a shift to lower carbon steels in their product mix. Some structural members are in the higher cost peritectic carbon region and result in higher cost and lower quality. The Total Activity Based Cost (TABC) methodology captures these actual steelmaking and hot rolling raw material and operational costs, energy costs, production rates, internal diverts and scrap, slab conditioning, repair and maintenance, scarfing, rework, customer complaints and external cost of quality. Through the adoption of these lower carbon Nb-containing structural materials, several design-manufacturing companies are initiating new offshore steel designs that will further provide improved overall lifetime and cost performance at reduced maintenance expense. Also, improved quench and temper Nb-bearing plate steels with increased yield strength levels are currently used in offshore platform fabrication. These high strength plate steels offer the opportunity to manufacture complex heavy-lift and fatigue-critical components for larger offshore structures without increasing the weight of the platforms. Deep-water structural steel platforms which are exposed to severe environmental loads offer further opportunities for Nb-bearing steels. Such critical components in the offshore structures require the steelmaker to adopt excellent steelmaking, slab casting and hot rolling operational practices in order to meet the stringent toughness requirements in the through-thickness of the plates.

The process metallurgy practices and operational performance during the melting and hot rolling of the steel plate greatly influences the final quality delivered to the offshore worksite. Steel cleanliness, low residual elements, appropriate carbon and microalloy chemistry and secondary ladle metallurgy, including vacuum degassing, are critical steps in the production of these value added offshore structural steels. The second key is the proper control of the reheat furnace during heating and soaking of the slabs prior to hot rolling which is quite often overlooked. During the hot rolling, the appropriate reduction schedules must follow correct operating practices. The process metallurgy, physical metallurgy and resultant properties are significantly affected by mill capabilities, mill practices, operational understanding and the culture of the steel mill. The third key is huge benefit often overlooked of homogeneous heating resulting in finer grain size and improved finishing temperature and coiling temperature control.

The chemistry is only one element of the complete process metallurgy chain. Process metallurgy practices that result in the optimum balance and production procedures are unique to each mill for a given chemistry. This combination is defined as Metallurgical Operational Integration (MOI©). [1] MOI is the system and methodology that links the product requirements to mill capability and process implementation. Product research and development from the laboratory to the mill production floor requires a disciplined transfer of technology from research to the mill. A thorough understanding of a mill's melting and heating strategy by steel grade, rolling mill horsepower limitations, reheat furnace practices and resultant thermal profiles throughout the rolling operation are key. Figure 1 schematically illustrates the Metallurgical Operational Implementation Model (MOI).

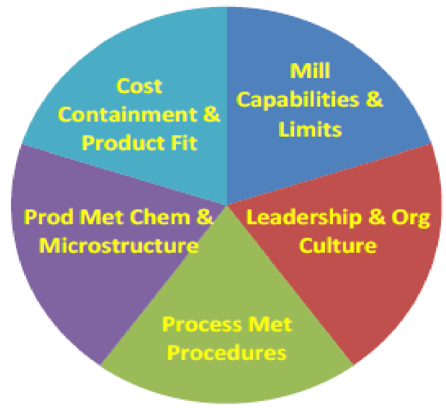

FIGURE 1: METALLURICAL OPERATIONAL IMPLEMENTATION (MOI)

OFFSHORE METALLURGICAL TRENDS

Within the offshore and other structural sectors, the global metallurgical chemistry trend involves a shift to lower carbon (0.03-0.05%C) Niobium (Nb)-bearing steels containing Chromium (Cr), Nickel (Ni), Copper (Cu) and/or Molybdenum (Mo) and/or Boron (B). This steel family meets strength levels of 420, 460, 500 and 550MPa exhibiting excellent toughness down to -60°C. Niobium additions in these grades can produce an acicular ferrite and/or bainitic microstructure when properly processed at the appropriate cooling rates and then isothermally annealed. Microstructures are shown below for a Mn-Mo-Nb-B offshore plate at various isothermal holds. Figure 2 illustrates Low carbon bainitic steel isothermal transformation microstructure after isothermally holding at various temperatures for 900s: (a) a small amount of allotriomorphic ferrite at 580℃, (b) acicular-like ferrite at 530℃ and (c) bainitic ferrite at 480℃. [2]

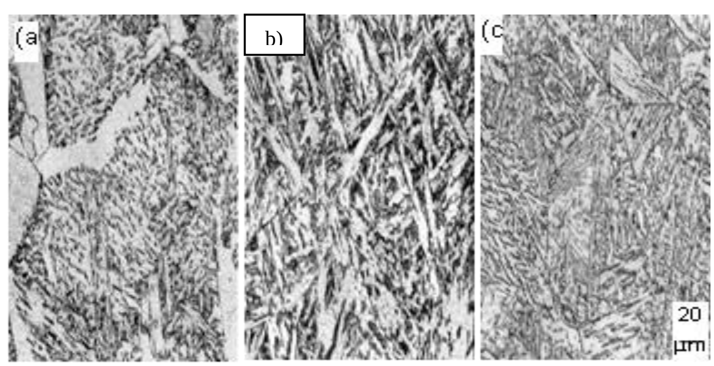

FIGURE 2: OPTICAL MICROGRAPHS OF MN-MO-NB-B STEEL

Yield strength exceeding 550MPa approaching 960MPa grade from low carbon bainitic steels are also possible and are developing in certain regions of the world for both onshore and offshore construction applications. For example, in China, a newly developed relaxation-precipitation-phase transformation control (RPC) process results in the packet size of bainite being refined to 3 microns in width and 6 microns in length. As a cost consideration, the 0.10%Nb concept in a Mn-Nb-B composition has been economically applied to develop a lower cost 550MPa-960MPa grade plate steels, even at 0.10%Nb. [2] The optimized thermo-mechanical control process (TMCP) metallurgy and appropriate tempering process are required. The role of solute and precipitate Nb promotes achievement of a very fine bainitic microstructure exhibiting superior toughness properties. As these Nb-bearing low carbon bainitic plate steels evolve, advanced gain refinement technology via the application of this RPC-Nb technology continues to be developed resulting in a lower cost leaner microalloy approach.

The optimized TMCP rolling process has been developed for 550-690MPa with increased Nb in the microalloyed offshore plate steels. The main composition of 550-690MPa grade low cost low carbon bainite steel is 0.03%-0.055 C, 1.7-1.9% Mn and 0.08%-0.11%Nb. Approximately 5-15 ppm boron is added to increase the hardenability ensuring a bainitic microstructure for a given cooling rate and similar to the globally well accepted HTP concept for pipeline steels. [3]

METALLURGICAL ROLE OF NIOBIUM

Niobium (Nb) can effectively influence the mechanical properties of steel in three ways: 1) through grain size refinement during the themomechanical hot forming, 2) lowering the austenite (γ) to ferrite (α) transition temperature (Ar_3) and 3) precipitation hardening. Grain refinement is the most effective mechanism that can simultaneously increase strength, toughness and ductility. Therefore, niobium is the most effective microalloying element, even when added at concentrations below 0.010%. In conjunction with the proper alloying technique and melting operation, the themomechanical rolling and cooling patterns are pivotal in successfully achieving an optimal balance between strength and toughness

LOW CARBON METALLURGY

A significant tonnage of hypo-peritectic (0.11%-0.16%C) steels has been applied in some offshore applications. Since specifications may allow up to 0.20%C, this outdated alloy design approach is being replaced by less than 0.10% C and is now well established for structural plate steels. Figure 3 illustrates a simple comparison between the effects of carbon on toughness.

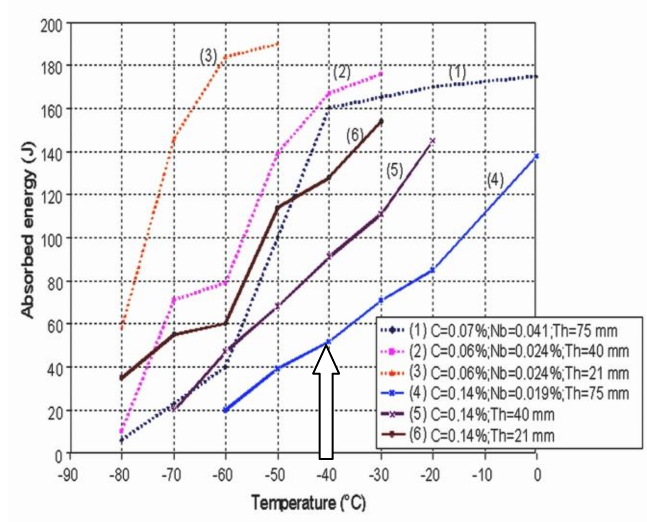

FIGURE 3: EFFECT OF C ON TOUGHNESS OF NB STEEL

For example, the 75 mm 355MPa plate at 0.07%C shows 160J impact strength at -40°C compared to 50J for the 0.14%C peritectic grade at similar Nb concentrations. [4] This nearly 300% increase in toughness at -40°C at the optimized Nb content is largely related to the carbon and the resultant finer grain microstructure from the Nb addition. The value of lowering the carbon content in many structural steel applications is quite often overlooked by the designer and it is not always promoted by the steelmakers. However, as more awareness evolves and designers specify C maximum concentrations, commercialization of the low carbon chemistry approach will replace the higher carbon chemistry because of better and more consistent mechanical properties, improved toughness, improved surface quality through avoidance of the unstable peritectic microstructure zone at the caster and improved weldability. In addition, the improved surface quality assists in enhancing the adhesion of coatings for the highly corrosive offshore structural steel environments.

As a result of the grain-refinement mechanism of Nb, higher yield strengths, improved weldability and improved fracture toughness is achieved through a lowering of the carbon content. It is incumbent on the designer and their responsibility to specify lower carbon level steels to improve the toughness, fatigue and weldability of the offshore platform structure without sacrificing strength. An opportunity exists to apply the niobium metallurgy already applied for some Nb-low carbon high strength pipeline grades (up to X80) to more offshore applications. These advanced high strength Nb-structural steel grades with lower carbon would also offer potential for improved performance in demanding seismic and high amplitude wave motion applications.

HIGHER C PERITECTIC OFFSHORE STEELS AND INCREASED COST OF PRODUCTION IMPLICATIONS

The metallurgical reasons for higher production cost for this 0.11-0.16%C (hypo-peritectic) microalloyed steel grade family compared to low carbon microalloyed grades relate to negative implications experienced at the steelmaking, casting and hot rolling steps of the production process as well as at the fabricators. Primary differences between low carbon and peritectic grades regardless of the choice of microalloy are:

1. Differences in solidification behavior during continuous casting
2. Casting requires tighter control of primary and secondary cooling for peritectic grades due to heat flux differences
3. Increased slab conditioning for peritectic grades due to uneven surface solidification resulting in a variable equiaxed chill zone that is closer to the surface compared to low carbon microalloyed grades
4. Maximum austenite grain size occurs in the 0.11-0.16%C range
5. Surface quality generally worsens in hot roll product
6. Increased slab scarfing, increased cost and potential to open cracks in peritectic grades
7. Often peritectic grades are normalized heat treated to homogenize the grain size, but not necessary in low carbon grades (eliminate heat treatment and reduce cost)
8. Grain size and mechanical property and toughness variability across the width and through the thickness is higher in peritectic grades
9. Peritectic grades are cast at slower speeds affecting productivity by as much as 10-20%
10. Increase in number of transition slabs and potential Downgrades in peritectic grades
11. Peritectic grades tend to exhibit more internal and centerline segregation, especially as Mn levels increase.

Figure 4 schematically illustrates these inter-relationships in order to achieve enhanced mechanical and microstructural properties at an acceptable margin. [5]

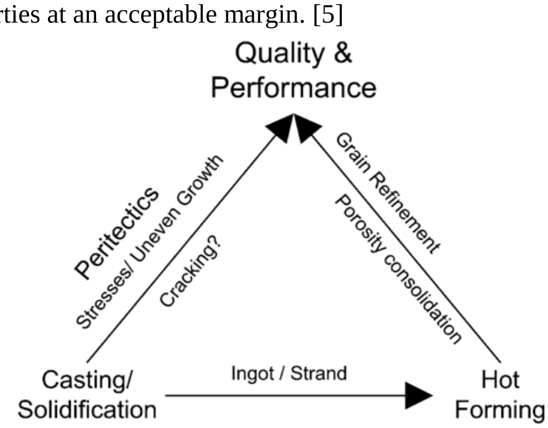

FIGURE 4: PERITECTIC STEEL IMPLICATIONS

Grain size and microstructure are of utmost importance in determining the strength, toughness, property variability and performance of a steel. Poor cast slab quality translates directly into increased internal and external cost of quality. These peritectic steel implications are of extreme importance and are incongruent with the global initiative to adopt high-speed continuous casting. At higher casting speeds, the resultant increase in productivity of steel translates into reduced operational cost per tonne, improved hot ductility during casting, and improved quality which is a priority in today's competitive global steel environment. Specifically, within the peritectic family of grades, the hypo-peritectic steels (0.11-0.16%C) impose a bottleneck for the high-speed casting in numerous operations around the world due to the strand contraction during peritectic solidification that causes non-uniform development of the shell in continuous casting mold.

World class mills consistently perform at 15-20°C superheat control during the continuous casting of microalloyed automotive sheet, pipeline plate and other critical plate products. Some plate mills that cannot hold such control during the casting of peritectic grades will encounter a higher incidence of slab cracking during the continuous casting process, regardless of the microalloy composition. This tight superheat control is quite difficult to achieve on peritectic grades for most mills and consequently increases their production and quality cost. By shifting below 0.10%C a more robust slab is produced. Hence, these difficulties are minimized and/or eliminated making the casting operation quite simpler allowing for a wider superheat operational window and more consistent quality. Figure 5 illustrates the fundamental inherent relationship of C and its effect on surface cracking.

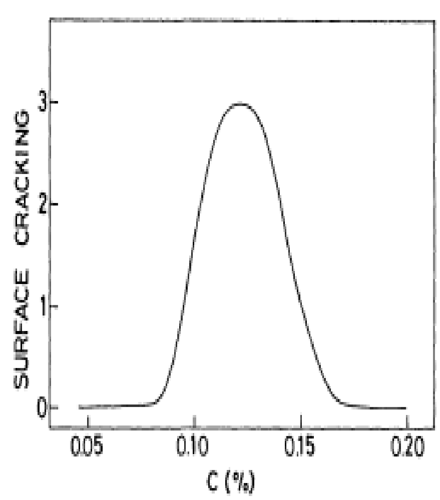

FIGURE 5: SURFACE CRACKING-CARBON RELATIONSHIP [6]

REHEAT FURNACE PROCESS METALURGY AND COMBUSTION EFFECT OF AUSTENITE GRAIN SIZE

The reheat furnace process metallugy directly affects the prior austenite grain size before the hot rolling deformation step. The uniform heating and soaking of slabs, billets and blooms in the reheat furnace operation is essential to obtain the proper prior austenite grain size before hot rolling. Although accepted universally in the steel community, the influence of slab reheating is typically not connected to poor toughness behavior (i.e. DWTT and Charpy). Variable austenite grain size often occurs in actual production for a variety of reasons. For example, the random overheating of the steel slabs, billets or blooms during the industrial reheat furnace operation causes abnormal grain growth. This randomness is quite predictable, but since proper dynamic reheat furnace control and practice adjustments are required in the moment to minimize these aberations. They are often ignored and no adjustments are made.

It is well accepted that different microalloys pin the austenite grain from coarsening to various sizes during these temperature excursions from a laboratory research basis. However, in the industrial process, this complex third order relationship relates the integration of the physical metallurgy of abnormal grain growth, the microalloy carbo-nitride pinning effect and the influence of the process metallurgy of reheat furnace temperature practices, variability and thermal inhomogoneity. The coherency of the microalloy precipitates with the matrix depends upon the microalloy content and precipitate type, precipitate stoichiometry, shape and volume distribution. The degree of pinning of the austenite boundary significantly affects the resultant strength and toughness balance in the final bar, plate or sheet product. The austenite grain size in the slab exiting the furnace before rolling is established. This prior austenite grain size directly influences the final grain size in the hot rolled product. The connection between inefficient slab, billet and/or bloom reheat performance and the consequential result of mechanical property variability in the final hot rolled product due to variations in prior austenite grain size is often not related or even considered in the laboratory and rarely accounted for in an industrial operation. This correlation is extremely complex and thus, the transfer of reheat time and temperature data and grain size measurements from laboratory experiments to actual industrial furnace operations are quite difficult to incorporate into a mill model.

The process metallurgical variables involved with the proper operation of the reheat furnace relate to the combustion efficiency, adiabatic flame temperature control, air to gas ratios and overall burner and combustion inlet and outlet fan performance is typically not adjusted for in the furnace model to capture actual furnace operation and conditions.

Figure 6 illustrates the primary effect of a change in the air to gas ratio of the combustion environment within the furnace to the inherent adiabatic flame temperature.

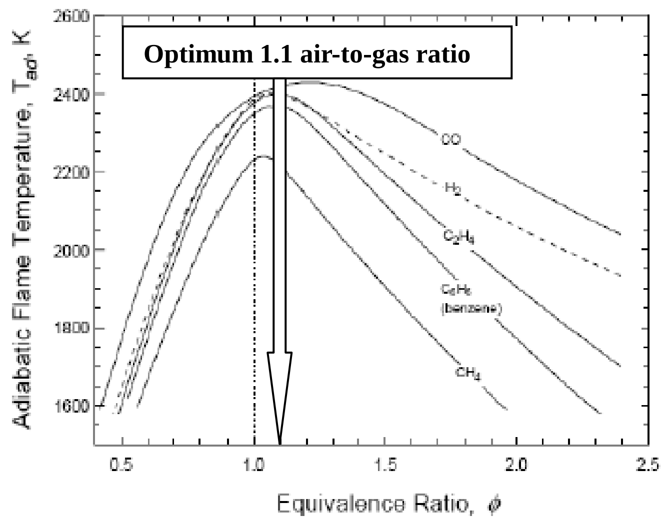

FIGURE 6: AIR TO GAS EQUIVALENCE RATIO VERSUS ADIABATIC FLAME TEMPERATURE

The highest adiabatic flame temperature translates into higher heat input, higher tonnage throughput and maximum furnace efficiency. The optimum air to gas ratio also develops an atmosphere in the furnace that is optimal for good surface quality and scale formation. As the air to gas ratio decreases, the adiabatic flame temperature decreases and then, the iron oxide scale thickness increases. Thicker scale on the slab surface acts as an insulating layer on the slab surface, thereby reducing the slab heat conduction efficiency. This variation in the heating process will significantly affect the resultant thermal homogeneity and thermal gradient from the surface of the slab to the center of the slab, as well as the austenite grain size and distribution.

The quality and efficiency of the reheat process has a profound effect on the austenite grain size and uniformity of grain size along the entire length of the slab. This step in the steelmaking process often receives low priority in the evaluation of product quality and mechanical property performance. The homogeneity and efficiency of heating is highly influenced by the air to gas ratio of the furnace burner combustion condition. The optimum air to gas ratio of 1.10 yields the highest adiabatic flame temperature. However, often in actual operations, cracked burner orifice plates, poor burner tuning and inefficient combustion fan performance contribute to variations in the air to gas ratio and hence, lower adiabatic flame temperatures. These situations have a huge effect on the optimal adiabatic flame temperature performance. Effectively, variable adiabatic flame temperature translates into variations in the heat input to the steel and inhomogeneous austenite grain size.

Inordinate amounts of time and valuable metallurgical resources continue to study the chemistry, TMCP rolling regimes and thermal practices as the root cause of the problem in not achieving desirable mechanical properties. In some cases, this analysis is valid and prudent. However, in other cases, the root cause analysis fails to relate inhomogeneity of heating and soaking within the reheat furnace to poor mechanical properties due to grain size. The chemistry, TMCP and thermal practices may be proper, but a variable prior austenite grain size and/or coarsening can result in variable final ferrite grain size. This situation translates into increased cost of diverts and scrap during the hot rolling operation due to variable mechanical properties. These additional costs of quality are enormous. [7]

Recent product development activity comparing different pinning elements such as Nb, V, Ti and Al have been studied. Figure 7 schematically represents this process/physical metallurgy relationship and analysis connection.

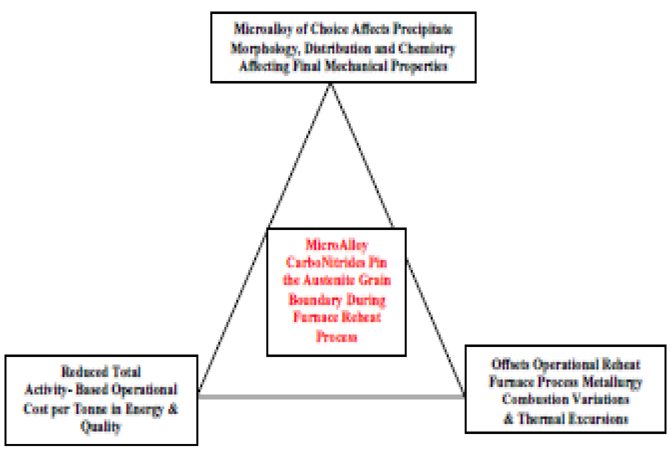

FIGURE 7: PROCESS METALLURGY-PHYSICAL METALLURGY (PM$^{2®}$) CONNECTIVE METHODOLOGY [7]

Successfully making the connection between industrial process metallurgy operational variables and the resultant physical metallurgy of the microstructural characteristics, precipitate morphology, precipitate chemistry and final properties is very complex. It is certainly a challenge, but is simplified somewhat when one connects the process metallurgy to the physical metallurgy.

The implications of thermal fluctuations during slab heating are variable and larger prior austenite grain size PAGS). Figure 8 relates the kinetic effects of increased and time at temperature on the PAGS.

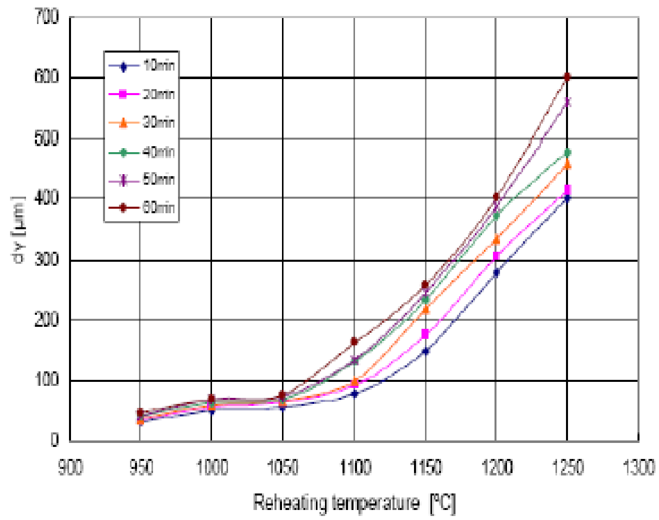

FIGURE 8: AUSTENITE GRAIN SIZE VERSUS REHEAT TEMPERATURE AND TIME [8]

Discontinuous austenitic grain growth is directly influenced by thermal variation conditions within the furnace caused by changes in the furnace performance and combustion efficiency. For example, the relationship between the air to gas ratio and the resultant austenite grain size may be correlated with the integration of Figure 6 and Figure 8 and finer homogeneous grain size translates into improved toughness. The furnace operational process metallurgy can be converted into the reheating temperature of the slab based on the air to fuel ratio for a given fuel (adiabatic flame temperature) and then into the estimated austenite grain size. For example, if the slab is being reheated at the optimum air-to-gas ratio of 1.10 with natural gas and one slab is at 1250ºC and the next slab is at 1225°C due to an air to gas variation of 0.05 in the furnace; then it follows that the austenite grain size would be approximately 600µm for the 1250ºC section at 60 minute heating time versus the adjacent section at 500µm grain size for the 1225°C condition (from Figure 8). Such differences in prior austenite grain size due to such thermal variations in combustion lead to a variable ferrite size in the final hot rolled product and hence, variable mechanical properties such as strength, yield-to-tensile ratio and toughness. Hence, the connection must be understood between the process metallurgy (i.e. increased reheat temperature and longer heating times) and the physical metallurgy result of increased austenite grain size.

Limited data is published on this inter-relationship between industrial furnace heating conditions, slab temperature, austenite grain size and toughness. This connection is a fruitful topic for future research and paper publications as it is an existing opportunity to enhance toughness with improved reheat furnace control. [7] Application of these practices will not increase operational cost and in fact may lower energy consumption and cost of quality due to more homogeneous heating. The starting point for austenite grain size control is in the heating of the slab for rolling. Homogeneous heating and soaking of slabs is vital in order to minimize temperature gradients (ΔT) between the surface and center of the slab and the ΔT from the front-end to back-end of the slab. Often during the rolling of C/Mn and microalloyed steels, variability of the ΔT from the front-end to the tail-end and/or high ΔT's from surface to center of the slab translate into variable mechanical properties within a coil or plate regardless of the mode of rolling (i.e., Steckel mill, plate mill or hot strip mill). In addition to less mechanical property variation, homogeneous heating translates into flatter and straighter plate (i.e. improved flatness and shape), better control of uniform and finer austenite grain size, solution of the microalloy carbonitrides and improved rollability. [9]

HOT ROLL MECHANICAL METALLURGY

Rolling schedules involve several different aspects of the rolling process; 1) the rolling line-up or grouping of the material to be rolled for best efficiency and quality, 2) the rolling practice (temperatures, thicknesses, times), and 3) the actual per pass parameters that the mill either sets up automatically through the Level 2 model automation or manually through the operator. The planning and organization of the rolling schedule or grouping is important for achieving the best mill efficiency, product quality and flatness. In addition to proper groupings by carbon equivalent, thickness, width and delivery date for creation of a properly balanced schedule, the roughing and finish pass reduction schedules must be aligned for productivity, metallurgy and final shape considerations. Regardless of the mill configuration, the per pass reduction schedule generated, should incorporate an increasing percent reduction in the roughing mill with steadily decreasing reductions in finishing mill as illustrated in Figure 9.

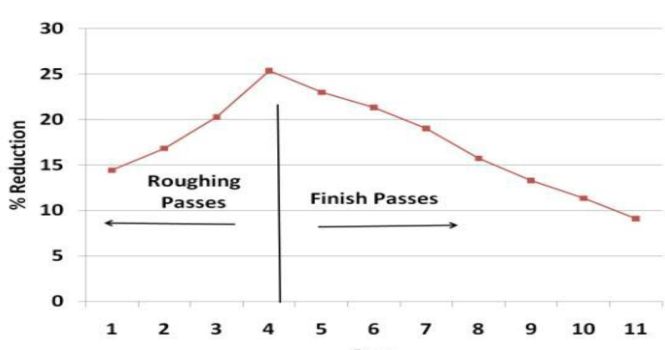

FIGURE 9: EXAMPLE REDUCTION PASS SCHEDULE FOR ROUGHING AND FINISHING [10]

When total reduction ratios are less than those described above, ignoring these reduction ratio to slab size relationships will typically result in mechanical property stability issues, poor Drop Weight Tear Tests (DWTT), poor Charpy impact performance and shape/flatness issues (due to non-uniform cross-sectional microstructural transformation). In order to accomplish this goal of cross-sectional grain size optimization, the rolling practices and mill per pass schedules must be designed to properly condition the austenite grains.

An example of the total reduction ratio as it relates to the mechanical ductility property of percent reduction in area is shown in Figure 10.

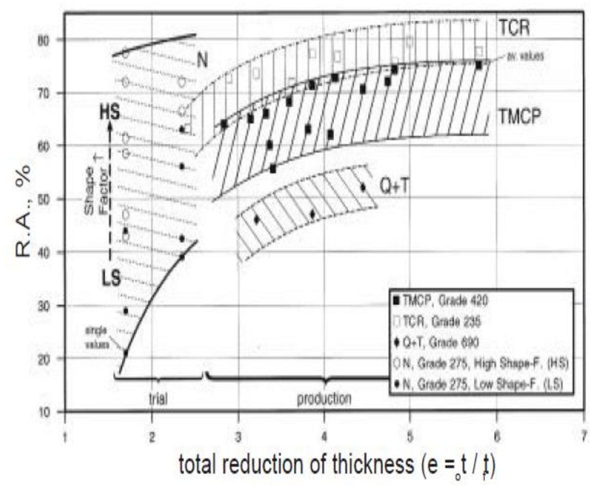

FIGURE 10: TOTAL ROLLING REDUCTION VERSUS PERCENT REDUCTION IN AREA [11]

Another important consideration relates to the mills' ability to fully penetrate the entire cross-section of the slab and deform grains at the slab centerline. This condition typically occurs when the slab is approximately one-half the starting slab thickness measured at the first official roughing pass. Regardless of the end product, one of the ultimate goals of the rolling schedule is to achieve the best mechanical property performance, optimize the alloy design and achieve optimum shape through the production of a fine/uniform cross-sectional grain size in the z-direction. Unfortunately, most rolling mill Level 2 model automation systems along with those mills that are manually controlled are not capable of properly addressing this major objective. In general, for maximum austenite conditioning a goal of 60% total reduction should be designed to develop the smallest diameter cross-sectional austenite grains at the end of the roughing pass as shown in Figure 11.

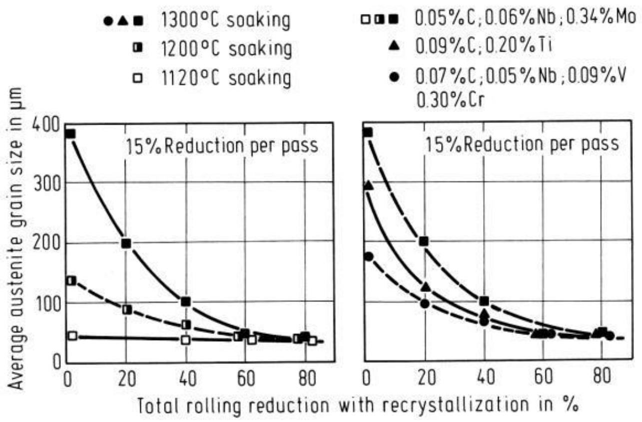

FIGURE 11: TOTAL REDUCTION IN ROUGHING VERSUS AUSTENITE GRAIN SIZE

The austenite grain size at the end of the roughing process sets the microstructure for the resultant microstructure during the finishing and the subsequent final grain size upon transformation. Approximately a 60% total reduction goal is calculated from the first roughing pass which defined as is the first rolling pass when product is rolled directly from the as-cast slab.

For structural plate steels used in offshore platform as well as bridge, ship and other construction plate steels, it is extremely important to achieve this 60% total roughing mill reduction goal and take the balance of reduction steps for total reduction in the finishing passes. This prescribed rolling reduction schedule will assist in the optimization of the strength, toughness and internal quality for these microalloyed grades. In higher strength steels, such as pipeline and offshore steels, a balance between roughing and finish pass reductions needs to be considered. The goal in the finishing mill is to achieve a minimum of 70% total reduction. When the rolling practice/schedule is designed with these goals of 60% in roughing and 70% in finishing total reductions, process optimization is realized. [10] Nearly all Level 2 automation models do not allow or incorporate this logic into their design. This reduction practice has to be done manually by the process engineer through either modifications or manipulation of the Level 2 automation model. [10]

Industrial trials were performed to compare the improper (normal) roughing schedules versus the modified schedule in Figure 12. The modified schedule produced acceptable strength, good mechanical properties and stable fracture toughness properties with over a 40% improvement in flatness.

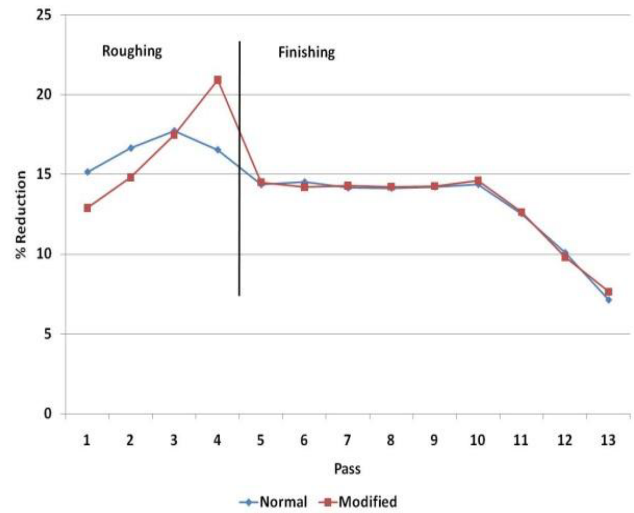

FIGURE 12: MODIFIED ROUGHING SCHEDULE FOR HEAVY GAUGE HIGH STRENGTH STRUCTURAL STEEL WITH IMPROVED FLATNESS

The initial slab temperature dictates the subsequent roughing and finishing mill rolling temperatures. It is important to avoid rolling below the Ar3. This situation may occur during the course of actual operations for a variety of reasons. Under such conditions, care must be taken to avoid too much deformation below the Ar3 temperature or pancaking of the ferrite grains will occur. While this condition is acceptable for strength, toughness will definitely deteriorate. Figure 13 shows an example of a pancaked ferrite grain region where too much deformation occurred below the Ar3 temperature. This coarser grain region within the microstructure leads to poor DWTT values.

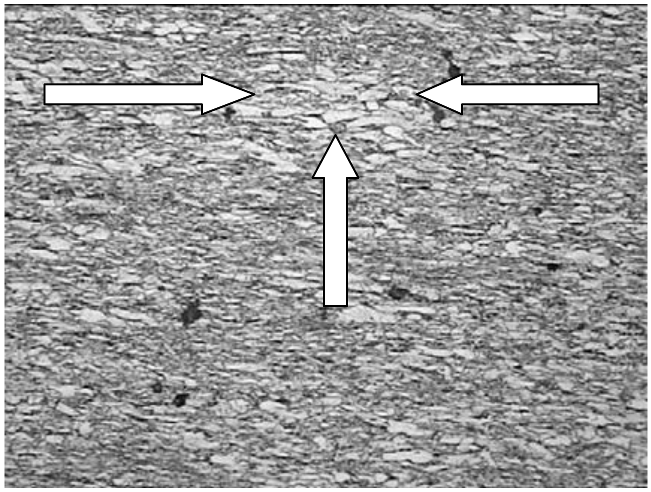

FIGURE 13: COARSE GRAIN DUE TO IMPROPER AUSTENITE CONDITIONING

THE EFFECT OF REHEAT TEMPERATURE ON TOUGHNESS

Several conditions have already been described which promote austenite grain growth at typical industrial slab furnace soak zone temperatures between 1100°C to 1275°C. Traditionally, Ti-Nb precipitates have been identified as key precipitates that pin grain boundary growth during the reheat process. Titanium is reported to prevent coarsening up to 1200°C. However, the problem experienced with titanium is that the grain boundary pinning is through the precipitation of the cuboidal titanium nitride precipitates formed during the casting process. Although effective in pinning the austenite grain growth, these large cuboidal TiN precipitates create stress risers in the steel during hot rolling. Since the TiN precipitates are cuboidal and have sharp corners, there is a stress riser at the corner point of the precipitate and the adjacent matrix. This condition results in lower toughness and fatigue properties compared to Nb and/or V-containing precipitates which are spherical and more coherent with the matrix. Recent research performed in Russia [12] exhibited that Nb is a key element for grain growth control. Submicron Nb carbonitrides suppress austenite grain growth at lower slab reheating temperatures. The effect of Ti additions on suppression of grain growth during low temperature slab reheating is negligible. Parameters of reheating such as duration and temperature were adjusted in order to maximize the effect of Nb microalloying and to obtain finer austenite grain before hot rolling. Industrial trials were conducted to evaluate the effect of reheating and deformation parameters on cold resistance of steel. Implementation of these results into production made it possible to produce plates with excellent properties including strength, toughness and cold resistance. It was determined that austenite structure of a steel containing 0.06% C, 0.21% Si, 1.8% Mn, 0.05% Nb, 0.017% Ti, 0.17% Mo with Ni, Cu, Cr additions prior to the rolling can be divided into three types depending on the heating parameters: fine-grained, coarse-grained, and mixed-grain.

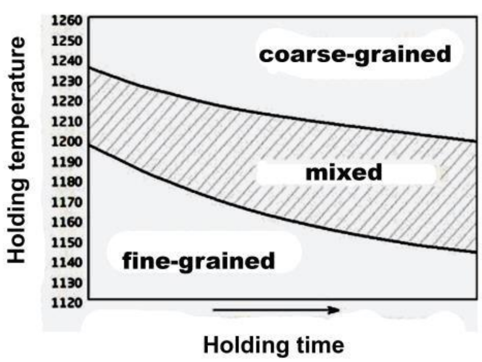

FIGURE 14: STRUCTURAL CONDITIONS OF AUSTENITE IN MICROALLOYED STEELS AFTER REHEATING [13]

A microstructure study was conducted to investigate the causes of abnormal grain growth based upon exceeding certain temperature and time parameters of the reheating process. Considering that the martensite packet size after quenching is governed by the size of the former austenite grain [13], it was concluded that after heating to 1160ºC the austenite structure is homogeneous and fine-grained, after heating to 1190ºC it is of mixed type, and after heating to 1250ºC it is homogeneous and coarse-grained, which complies with the results presented in Figure 14.

Results of these laboratory studies were then confirmed during industrial trial production of 40-mm plates with a specified minimum yield strength (SMYS) of 450 MPa at the 5-m hot rolling mill of Vyksa Steel Works. [12] The chemical composition of steel was 0.06% C, 0.20% Si, 1.6% Mn, 0.03% Nb, 0.016% Ti, and additions of Ni, Cu, Cr (Mo). A two-stage TMCP process was imposed with the proper consistent reduction parameters and various reheating modes (temperature and duration). Reheating temperatures ranged between 1100°C and 1200°C. Slabs were held in a continuous furnace within 5-12 hours. Drop-weight tear tests (DWTT) were performed to evaluate cold resistance. The results of the industrial trials are presented in Figures 15 and 16. [12]

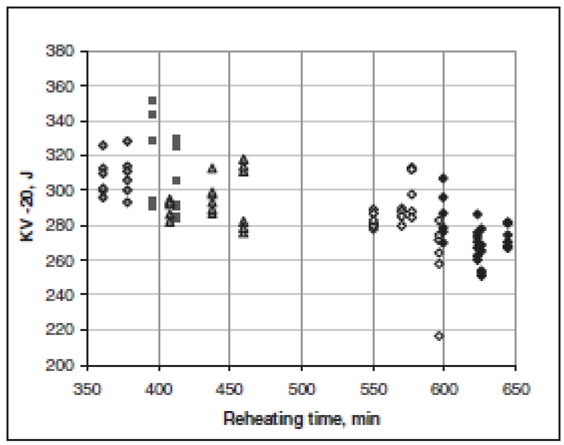

FIGURE 15: KV-20°C - J AS FUNCTION OF TIME AT 1170°C

Figure 15 shows the time parameter effect and deterioration in toughness for slabs held at 1170°C for times exceeding 500 minutes. The influence of reheating temperatures on %DWTT and mechanical properties is illustrated. There is more scatter from 40% to 90% DWTT (at -20°C test temperature) for the high reheat soak zone temperatures (1180°C-1220°C) compared to the medium and lower holding temperatures with scatter from 75% to 100% DWTT at -20°C.

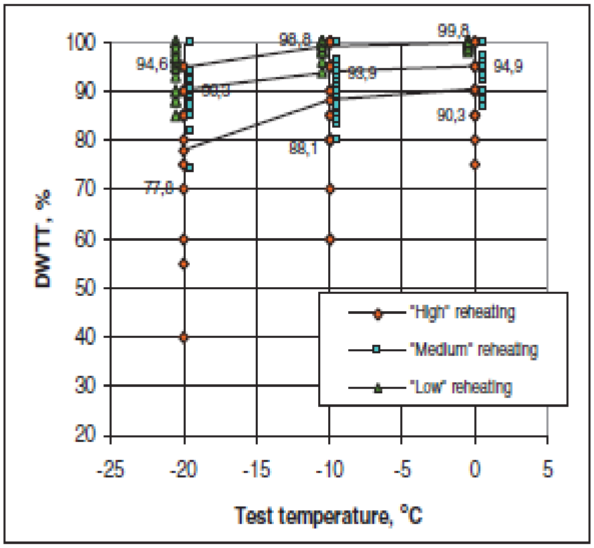

FIGURE 16: SHEAR AREA OF DWTT VS. DWTT TEST TEMPERATURE [12]

CONCLUSIONS

There is a direct link between the reheating history (i.e. temperature and time), austenite grain size, Nb grain boundary pinning, rolling reduction schedule and mechanical properties, specifically toughness as measured by DWTT or Charpy at low temperatures. These connections are critical for the successful melting, casting, reheating and hot rolling of offshore plates. These operational parameters become even more sensitive and require even less process parameter variability for heavier thickness offshore platform plates (i.e. exceeding 100mm).

Reduced reheat soak zone temperatures in the 1150°C to 1200°C and holding times less than five hours are recommended with optimum control of the air-to-gas ratio at 1.10 ±0.05 to minimize variations in the adiabatic flame temperature of the burners, The tighter this control then the more homogeneity of temperature and hence, austenite grain size uniformity from the front-to-back of the slab as well as through the thickness of the slab (i.e. z-direction).

The mechanical metallurgy is enhanced when a thoroughly soaked slab is presented at the roughing mill. . When the rolling practice/schedule is designed with goals of 60% reduction in the roughing step and 70% in finishing total reduction, then process optimization is realized and toughness is enhanced through the thickness of the plate.

The continuous casting is indigenous to the successful production of these high strength offshore grades. As more awareness evolves and designers specify C maximum concentrations, commercialization of the low carbon chemistry approach will replace the higher carbon chemistry due to better and more consistent mechanical properties, improved toughness, better plate flatness, improved surface quality by avoiding the peritectic zone at the caster and improved weldability. Peritectic grades (between 0.11%-0.16%C) inherently exhibit higher surface cracking incidence which is related primarily to the thin equiaxed chill zone which is quite weak as the strand descends through the unbending zone of the continuous caster and is vulnerable to cracks.

REFERENCES

1. S. Jansto, "Cost Effective Microalloy Structural Steel Balance of Process Metallurgy and Materials Engineering," *MS&T*, Pittsburgh, PA, October 2008.

2. C. Shang, X. He and H. Hou, "The Development of High Performance Low Carbon Bainitic Steels," *Niobium Bearing Structural Steels*, TMS, October 2010.

3. K. Hulka, J.M. Gray, *Nb Science and Technology*, TMS, 2001, pp. 587-612.

4. S. Jansto, "Niobium Market and Technical Development for Civil Engineering Structural Applications," *International Symposium of HSLA Steels for the Construction Industry*, Tianjin, China October 22-23, 2007.

5. H. Nasari, "On Peritectic Reactions and Transformations and Hot Forming of Cast Structures," *Royal Institute of Technology (KTH*), Ph.D. thesis, Stockholm, Sweden, 2009.

6. T. Saeki, et.al., *Tetsu-to-Hagane*, 68 (1982), p.1773

7. S. Jansto, "Operational Metallurgy Practices to Minimize Abnormal Austenite Grain Growth during the Reheat Furnace Process," *Materials Science & Technology Conference*, October 2012.

8. L.Nemethova, *Acta Metallurgica Slovaca*, 15 (**2009**), 3. pp. 173-179.

9. D. Stalheim and S. Jansto, "Hot Rolling Operational and Metallurgical Considerations for Value-Added Microalloy Bearing Steels," *Proceedings of the 10th International Conference on Rolling Steels*, Beijing, China, 2010.

10. D. Stalheim and S. Jansto, "Key Operational and Metallurgical Parameters for Production of Structural Plate Steels," *The International Symposium on the Recent Development in Plate Steels*, AIST, June 19-22,2011. Winter Park, Colorado.

11. A. Streisselberger, V. Schwinn, R. Hubo., W. Schutz, "Microalloyed Structural Plate Rolling, Heat Treatment and Applications," *Proceedings of the International Symposium Niobium 2001*, Orlando, FL, USA, 2001.

12. M. Yu. Matrosov, S.V. Golovin, D.A. Ringinen, V. Ilynsky, S. Yu. Nastich, A.A. Kichkina I.V. Lyasotsky, *HSLA Steels 2015, Microalloying 2015 & Offshore Engineering Steels 2015*, Hangzhou, China.

13. Ringinen D.A.; Chastukhin A.V.; Khadeev G.E.; Efron L.I.; Il'inskiy V.I., "Evolution of Austenite Grain Structure and Microalloying Element Precipitation During Reheating of Steel of Strength Class K65 (X80) for Rolling," *Metallurgist*, Vol. 57, Nos. 11-12, March, 2014.

