TMCP COMBUSTION METALLURGY*

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Abstract

The market demand for reduced fuel consumption and CO_2 emissions in the automotive, energy and construction sectors have further increased the demand for new and advanced higher quality microalloyed grades produced via TMCP. The technological integration of the process and physical metallurgical advancements of value-added niobium (Nb) microalloyed thermo-mechanical controlled process (TMCP) steels continue to be developed and is an important element for these more demanding end user requirements and cost-effective steel production. The reheat furnace process step has a profound effect on the TMCP performance, final hot rolled steel quality and mechanical property consistency during the production of hot rolled steels. The uniformity of heating applied across the entire width, thickness and length of the slab or billet is essential in the successful achievement of consistent customer properties regardless of the chemistry. The resultant ferrite grain size in the final hot rolled product is significantly governed by the initial prior austenite grain size. However, the transition from laboratory melted and TMCP hot rolled heats to the production scale is often quite challenging. Aberrations in the reheating process step at the industrial furnace are often the root cause of mechanical property quality issues. These combustion process metallurgy parameters connect directly to the resultant TMCP product quality and is defined as Combustion Metallurgy® (CM®).

Keywords: Adiabatic flame temperature; Air-to-gas ratio; Combustion; Quality.

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1 INTRODUCTION

The proper thermomechanical controlled processing (TMCP) of steels produces flat rolled products with exceptional toughness, yield-to-tensile ratios, good weldability and excellent ductile-to-brittle transition impact behavior in a variety of applications. TMCP process metallurgy involves the triad of slab reheating practices, proper reduction schedules for appropriate recrystallization type during deformation and accelerated cooling rates (exceeding a minimum of 5°C/second) on the flat rolled products. All three process elements contribute significantly to the toughness behavior and fracture resistance to crack propagation. However, often in industrial operations, variations in the three triad process parameters will offset the optimal achievement of toughness, strength and microstructure.

Specifically, the reheat furnace operation including the thermodynamics, kinetics and combustion conditions in the actual production process receives insufficient attention. This factor is often not given high priority when evaluating mechanical property diversions on an industrial scale. Corrective actions and operational practice recommendations are presented in order to minimize inhomogeneous heating in the rehat furnace which often results in inferior product quality and toughness variations in the through-thickness-direction of the final hot rolled product.

2 THERMODYNAMICS AND KINETICS OF COMBUSTION

Combustion is a self-propagating exothermic oxidative chemical reaction, mostly in the gas phase, producing light, heat and smoke in a nearly adiabatic flame front. These phenomena may be divided into two groups: 1) equilibrium behaviour and 2) kinetics. Combustion thermodynamics focuses on the physico-chemical phenomena encompassing fuel/air ratios, heating values, maximum work obtainable, exhaust composition and O2 levels. Complementary, the combustion kinetics focus on the mixing process, flame geometry, ignition, extinction, propagation and stability. The study of combustion is based on the more general subject of thermodynamics of chemical reactions, usually called thermochemistry. The combustion reaction in the reheat furnace, with a focus on the thermodynamics of a fuel-and-air gas-phase reaction is indigenous to the process of reheating slabs blooms and billets.

In the combustion reaction, at least 9.5 m^3 of air are required for the complete combustion of 1 m^3 of methane at same p-T conditions (the molar stoichiometric air/fuel ratio is A0=9.5), with a maximum heat output of 55 MJ/kgCH$_4$ (or 37 MJ/m^3, the higher heating value of methane) that would decrease as the exhaust temperature increases until a maximum when no heat is exchanged, at the maximum temperature of 2250°K (the adiabatic combustion temperature for the optimum stoichiometric mixture). The exhaust composition for stoichiometric mixture consists of 71% by volume of N$_2$, 19% H$_2$O, 9% CO$_2$, and much less than 1% of undesirable gases defined as emissions. The emissions are noxious to the health: CO, NO, NO$_2$, aromatic-hydrocarbon vapors and maybe soot. The reheat procedure for slabs, billets and blooms before hot rolling is a fundamental and critical step in the hot roll process. The combustion and the heat transfer process influence the deformation schedule, recrystallization as well as the resultant mechanical properties of the final hot rolled product.

In the reheat furnace, the slab is actually heated via radiation off the refractory walls of the roof and sidewalls. The roof and sidewall refractory absorb heat from the flames emitted from the combustion burners. The adiabatic flame temperature (AFT) is affected by the fuel type, burner efficiency and air to gas equivalence ratio.

The highest AFT translates into higher heat input, higher production throughput and maximum furnace efficiency. The optimum air-to-gas ratio also develops a furnace atmosphere that is conducive for good surface quality, high heat penetration into the slab and optimal scale depth and viscosity. Figure 1 illustrates the effect of different air-to-gas ratios (i.e. equivalence ratios) on the adiabatic flame temperature for different gases.

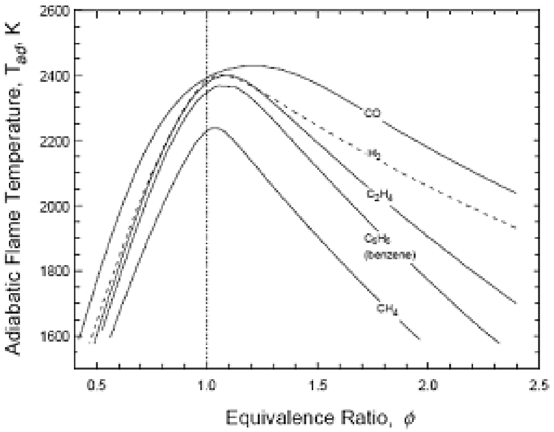

Figure 1. Air-gas equivalence ratio.

Since most furnaces consume natural gas, the maximum adiabatic flame temperature of 2250°K occurs at approximately 1.10 equivalence ratio (10% excess air). Under these conditions, approximately one-half of the heat generated from the combustion of the fuel heats the steel. As the air to gas equivalence ratio increases, combustion efficiency declines and AFT decreases. There are several operational reasons that adversely increase the equivalence ratio. [1] Several furnace factors can create higher equivalence ratios resulting in improper heating of the steel and longer heating times:

- Cracked burner orifice plates leading to sub-optimal flame temperature
- Refractory cracks in furnace roof and/or sidewall leading to air infiltration into the furnace
- Low furnace pressure due to inefficient combustion fan mechanical performance (bearings, out-of-balance, component wear)
- Reduced working volume in the bottom zone of preheat and reheat section due to scale buildup
- Improper dilute oxygen enrichment at combustion burner tip
- Scale formation and viscosity

Most commercial fuels are hydrocarbons. According to the stoichiometric ratio for full oxidation of a fuel, air/fuel mixtures fed to a combustor are classified as:

- Lean mixtures (little fuel content, excess of air).
- Stoichiometric mixtures (with the precise or theoretical amount of fuel)
- Rich mixtures (more fuel than needed, but excess fuel will pyrolyze to small-molecule fuels, and only small molecules appear at the exhaust).

It important to understand that kinetics is what ultimately controls the combustion reaction, effectiveness and efficiency. Thermodynamics indicates if the reaction is natural (i.e. may proceed in an isolated system) or artificial (i.e. requires some exergy input from outside). Thermodynamics ensures that a fuel and air may naturally react, but if the kinetics are too slow, the combustion reaction is hindered. Two extreme cases of mixing are considered in combustion: combustion in a premixed system and combustion in the common-interface layer where non-premixed fuel and air come into contact. Also, the proper temperature and reheat time is critical to ensure that the various microalloy and/or alloy elements in high strength TMCP processed grades are properly put into solution in actual reheat furnace production conditions before rolling at the roughing and finishing mill.

3 GLOBAL REHEAT FURNACE OPERATIONS

Numerous furnace operations throughout the world operate at both high reheat zone (>1150°C) and soak zone furnace temperature (>1225°C), thereby overheating both plain carbon steels and microalloyed steels leading to abnormal grain growth. Observations made at numerous mills around the world find high temperature furnace operation even more prevalent on higher carbon steels exceeding 0.20%C. The cause and effect relationship of these poor furnace heating practices have a detrimental effect on steel quality due to abnormal and variable grain size and inhomogeneous heating through the slab thickness. Coarser austeinte grains translate into coarser ferrite grains in the final hot rolled product. Also, overheating of steel, results in thicker scale formation. The metallurgical consequences of thick scale formation goes beyond simple surface quality issues and translates into mechanical property variability due to improper heating of the slabs before hot rolling. Figure 2 shows the relationship between the mass increase (i.e. scale formation), which is the weight (grams) of scale per meter^2 of slab, at 1250 and 1300°C.

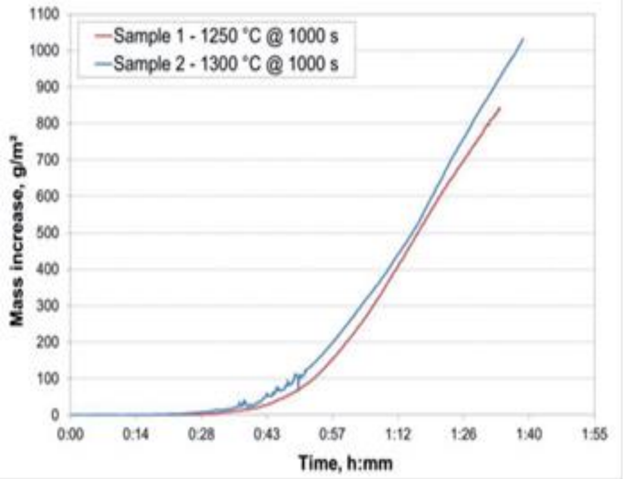

Figure 2. Increase in mass over time for oxidation at 1250° and 1300°C in methane combustion atmosphere [2]

Observations made at numerous mills around the world find high temperature furnace operation is often prevalent at mills producing HSLA microalloyed steels and higher carbon steels exceeding 0.20%C. Niobium is effective in delaying austenite grain growth when high temperature overheating conditions occur. Within the furnace operation, heating and combustion zone temperatures are typically increased to offset low combustion efficiency issues in an attempt to increase productivity. This approach however is flawed as the slabs are not homogeneously heated. The problem is then one of sacrificing quality (i.e. mixed and coarse austenite grain size) for increased throughput measured in tons per hour. Some mills increase soak zone temperatures (optical pyrometer readings in the furnace) approaching 1250-1275°C (1300°C in some regions of the world) which translates into steel surface discharge temperatures approaching 1225-1240°C and thus the initiation of severe austenite grain growth. From a practical operational perspective, soak zone temperatures exceeding 1250°C is extremely deleterious to steel surface quality, toughness, yield and mechanical property and cost performance. The decrease in yield is due to formation of a heavy iron oxide scale. This scale can be several millimeters in thickness and converts to as much as 1 to 1.5% of yield loss. The relationship between furnace temperature, long heating times and scale thickness are illustrated below in Figure 3.

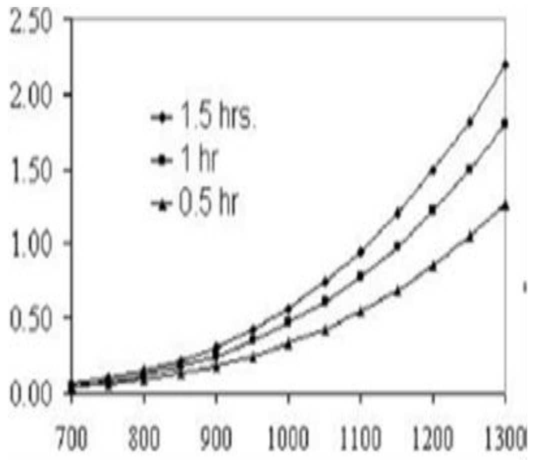

Figure 3. Scale thickness (mm) versus temperature [3]

It is apparent from Figure 3 at 1200°C, an increase in hold time from 1.00 to 1.50 hours will increase the scale thickness by nearly 30%. The decrease in yield is due to formation of a heavy iron oxide scale. This scale can be several millimeters in thickness and converts to as much as 1 to 1.5% of yield loss. This loss in product translates into millions of dollars of scrap and reduced yield on an annual basis. Scale behaves as an insulator and consequently, the thicker the scale then a reduction results in the thermal conductance of heat absorbed by a given slab. A second factor involves the influence of the air-to-gas ratio. As the air-to-gas ratio increases, the AFT decreases and then due to more oxygen in the furnace environment, the iron oxide scale thickness will increase. Heat conductance requires longer heating times. The scale layer is an insulating layer on the slab surface, reducing the slab heat conduction efficiency. Under these conditions, longer soaking times are necessary to ensure proper heating of the center of the slab. Longer soak times lead to increased prior austenite grain size. This variation in the heating process will significantly affect the resultant thermal homogeneity and gradient from the surface of the slab to the center of the slab, as well as the austenite grain size and distribution.

Scale formation is a function of the material chemistry, furnace environment, oxygen content in the flue gases, furnace temperature and the heating time required. Furnace temperature and oxygen content are both controllable parameters. The oxy-fuel technology has been implemented as an important process control tool to facilitate the reduction in exposure time during the heating operation. Customer experience and laboratory tests indicate reduced levels of scale formation when proper heating practices are executed. The scale that is formed has the right properties and thickness for simple and effective scale-breaking and removal prior to rolling or forging operations. [4] In some cases, it is possible to reduce or eliminate some downstream processing as well. One customer report that the surface properties improved so much with the oxy-fuel combustion practice that their skin-pass operation could be eliminated reducing operational cost. [5]

The reheat furnace process metallurgy directly affects the prior austenite grain size before the hot rolling deformation step. Although accepted universally as a vital processing step in the steel community, the influence of slab reheating is typically not connected to poor toughness results (i.e. low DWTT and low Charpy values). The random overheating of the steel slabs, billets or blooms during the industrial reheat furnace operation causes abnormal grain growth. This randomness is sometimes predictable, but since proper dynamic reheat furnace control and practice adjustments are required in the moment to minimize these aberrations, no changes are made. Many mills often ignore the reheat furnace combustion aberrations and no adjustments are made. Consequently, mechanical properties through the thickness and across the width will vary considerably and deteriorate, especially toughness, yield-to-tensile ratios, stretch flangeability, fracture toughness and fatigue properties.

4 EFFECT OF REHEAT FURNACE COMBUSTION METALLURGY ON TMCP ROLLED PLATE MECHANICAL PROPERTIES

Results of several studies confirmed the importance of proper furnace control in industrial trial production of 40-mm plates with specified minimum yield strength (SMYS) of 450 MPa at the 5-meter hot rolling mill of Vyksa Steel Works in Russia. [6] The chemical composition of the 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 implemented with the proper consistent reduction parameters and various reheating modes (temperature and duration). The objective of this trial was to evaluate the effect of reheat temperature and duration time on the impact toughness behavior of a Nb-microalloyed steel. The reheating temperatures ranged between 1100°C and 1200°C. Slabs were held in a continuous furnace between 5-12 hours. Impact toughness (Kv at -20°C) and drop-weight tear tests (DWTT) were measured to evaluate cold resistance toughness behavior from the industrial trials. [6]

Figure 4 shows the time parameter effect at a low reheat temperature of 1170°C and the associated deterioration in toughness for slabs held over 500 minutes. Also, greater than 500 minutes heating time generally exhibits lower average toughness compared to the less than 500 minutes heating time. The reheating is coupled with the appropriate reduction schedule to achieve proper recrystallization phenomena.

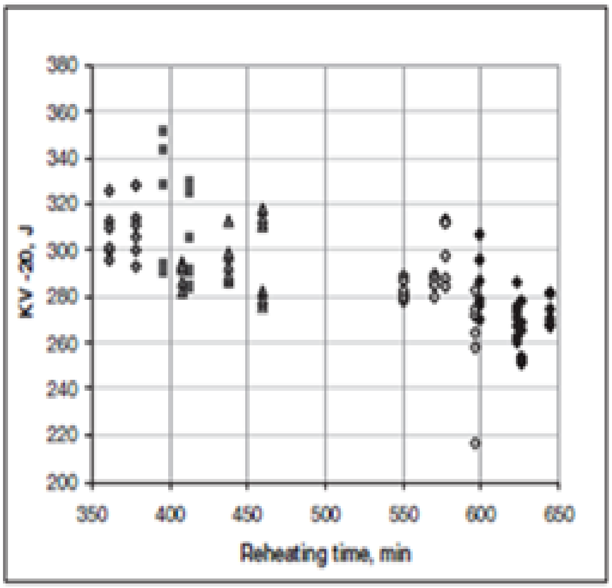

Figure 4. KV-20°C - J as function of time at 1170°C [6]

This recrystallization phenomena are especially important for plate production, since even modern high-power mills cannot provide at times full multiple recrystallization aimed at refining prior coarse-grained austenite structure, typical for high-temperature rolling. This blend of proper low to medium reheat practice and mechanical deformation schedule set the parameters for optimization of the finest grain size through the plate thickness. The % drop weight tear test (DWTT) is the ultimate measure of the success or not in the final rolled plate product toughness and ductile shear behavior. The influence of reheating temperatures on %DWTT is illustrated in Figure 5. [6]

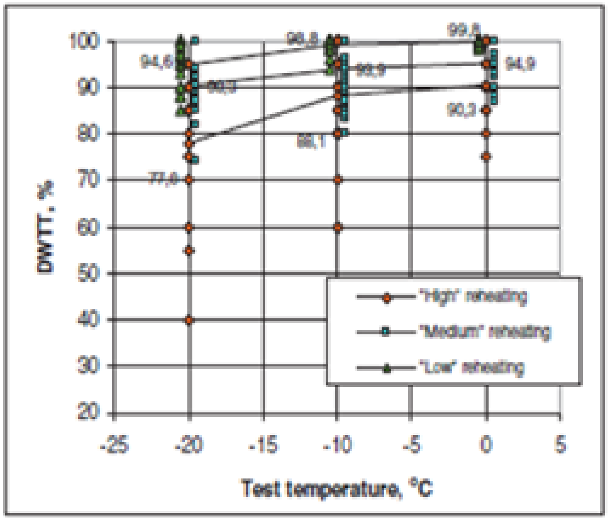

Figure 5. Shear area of DWWT versus DWTT test temperature [6]

5 COMBUSTION METALLURGY PROCESS TECHNOLOGICAL LINKS

This process metallurgy link between reheat furnace operational variables, resultant efficiency of heating and soaking, PAGS and final hot rolled ferrite grain size is a critical quaternary relationship which warrants more in-depth study and analysis. Finally, this connection and methodology between combustion effectiveness, metallurgy and its effect on austenite grain size is emphasized with the objective of improving quality and mechanical property consistency.

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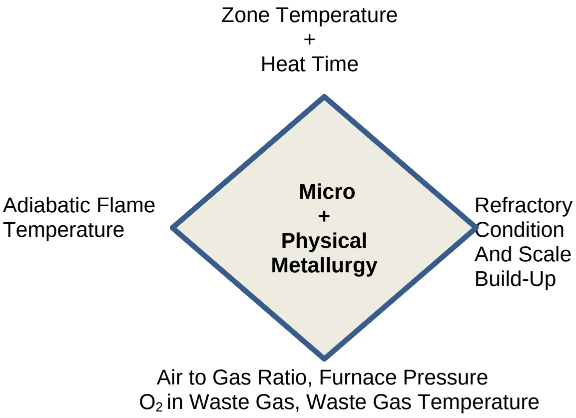

Figure 6. Process and Physical Metallurgy Connection [7]

Combustion conditions and environment within the bottom, top and soak zones of the reheat furnace significantly influence the Microstructure and Physical Metallurgy of the final hot rolled product. Some of the predominant metallurgical factors affected include:

1) Prior Austenite Grain Size
2) Uniformity of Grain Size through Thickness
3) Recrystallization Behavior
4) Impact Properties through Thickness

The relationship between inhomogeneous heating and the resultant mechanical properties is often not reported. The metallurgical consequence of a mixed and/or coarse austenite grain translates into variable ferrite grain size in the final rolled product. The mechanical property implications involve yield and tensile strength variability, sporadic formability and significant impact toughness scatter through the thickness of the plate. The reheat furnace operation is receiving more attention due to its significant effect on the differences in impact properties between the ¼ - point and the centerline-point in hot rolled plate. This variability increases as the plate thickness increases. Table 1 illustrates the difference in toughness between the ¼ point and the centerline for a 0.05%Nb and less than 0.10%C-48mm thick plate for a Q550 and Q690 LCLA (Low Carbon Low Alloy) plate rolled on an industrial plate mill.

During the reheat process, several conditions have already been described which promote austenite grain growth at typical industrial slab furnace soak zone temperatures between 1150°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 on a laboratory scale. However, the problem experienced with titanium is that the grain boundary pinning from the precipitation of the cuboidal titanium nitride precipitates formed during the casting process can act as crack initiators under impact loading. Although effective in pinning the austenite grain growth during heating, there is a trade off in that 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. Figure 7 below illustrates the cuboidal shape of the TiN precipitates and the spherical 3-5 nanometer NbC precipitates attached to the TiN precipitate. [7]

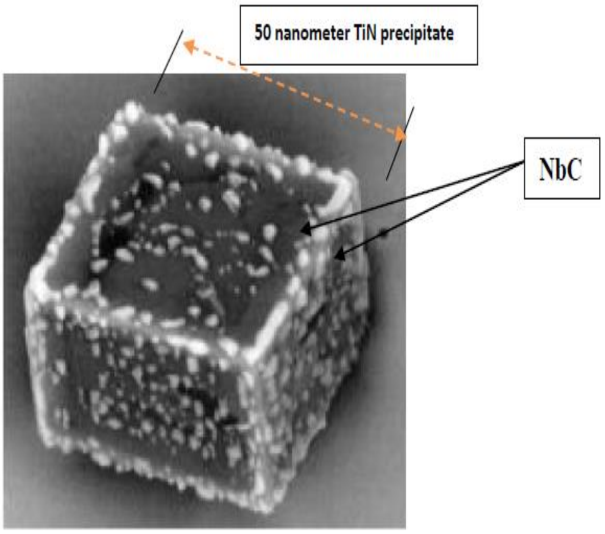

Figure 7. 50 nm cuboidal titanium nitride precipitate with spherical NbC epitaxial precipitation

As these TiN precipitates are quite brittle due to a high microhardness, they act as crack initiators at high strain rate and impact loading. 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 [6] exhibited that Nb is a key element for grain growth control. Submicron Nb carbonitrides are softer particles and will suppress austenite grain growth at lower slab reheating temperatures. The effect of Ti additions on suppression of grain growth during low temperature slab reheating (less than 1225°C) on an industrial scale is found to be negligible. It is evident that the role of titanium microalloying in formation of fine-grained microstructure is insignificant, since coarse particles of titanium nitride are located at considerable distance from each other and cannot act as a significant obstacle to the movement of boundaries. However, in the case of Nb, parameters of reheating such as duration and temperature can be properly adjusted in order to maximize the effect of Nb microalloying and obtain finer austenite grain before hot rolling. Coupling the proper reheat temperature with the appropriate reduction schedule leads to a very fine homogeneous grain size through the thickness of the slab and plate. Industrial trials were conducted to evaluate the effect of reheating and deformation parameters on cold resistance behavior of the 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 the austenitic microstructure 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: 1) fine-grained, 2) coarse-grained and 3) mixed grain (Figure 9).

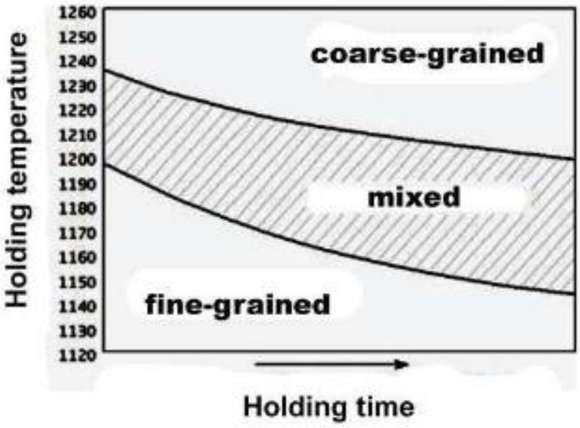

Figure 8. Structural conditions of austenite in microalloyed steels after reheating [8]

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 [8], 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 coarse-grained, which conforms to the results presented in Figure 5.

6 REHEATING FURNACE OPERATION AND ITS EFFECT ON AUSTENITE GRAIN SIZE

The quality and efficiency of the reheating 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.

Discontinuous austenitic grain growth is directly influenced by such thermal variation conditions within the furnace caused by variable air to gas ratios. The adiabatic flame temperature variation with the air to gas ratio (Figure 1) and the effect of temperature on the prior austenite grain size is illustrated below in (Figure 9). [9] The connection between the process metallurgy and the physical metallurgy is made.

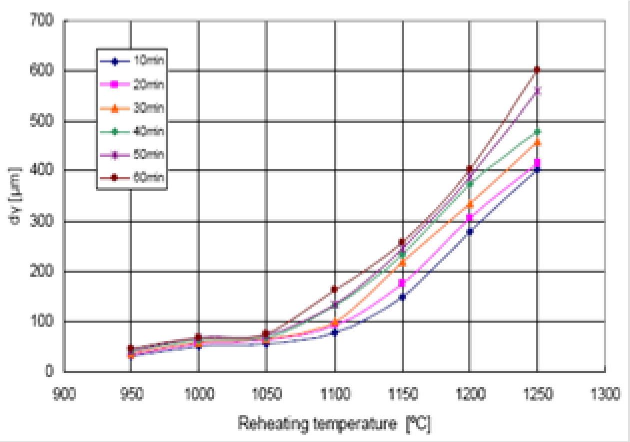

Figure 9. Austenite grain size versus furnace temperature

For example, the relationship between the air to gas ratio and the resultant austenite grain boundary may be correlated with the integration of these two figures (Figure 4 and Figure 10. The furnace operational process metallurgy can be converted to the reheating temperature of the slab and then into the estimated austenite grain size. For example, if one section of the slab is at 1200ºC and the adjacent section is 1225°C due to an air to gas variation 0.05; then it follows that the austenite grain size would be approximately 325µm for the 1250ºC section versus the adjacent section at 280µm grain size for the 1225°C region. 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.

7 MICRONIOBIUM ALLOY APPROACH TO BALANCE IRREGULAR FURNACE CONDITIONS

An application of the Nb pinning effect when temperature conditions are excessive has been successfully demonstrated in both medium and high carbon steels. The recently developed application of the MicroNiobium Alloy Approach® in medium and high carbon steel long product, sheet and plate steels enhances both the metallurgical properties and processability as well as reducing the operational cost per tonne of production. The process and product metallurgy improvements relate to the Nb-pinning effect at the austenite grain boundaries which offset thermal aberrations in the reheat furnace. Mills are often quite reluctant to publish such findings and benefits derived from such Nb micro-additions to improve the robustness of the final hot rolled product by minimizing austenite grain growth. The metallurgical mechanism of the MicroNiobium Alloy Approach in this medium carbon example is retardation of austenite grain coarsening during reheat furnace soaking of the billets, slabs or shapes before rolling. Variable grain size is induced by temperature fluctuations and inhomogeneity during the heating of the slabs in the reheat furnace. Such fluctuations can occur due to variations in the air-to-gas ratio, directly affecting the adiabatic flame temperature and heat input into the slabs. This approach contributes to the achievement of an ultra-fine grain, homogeneous higher carbon microstructure that exhibit superior toughness, high strength, less mechanical property variation in the final hot rolled product through the thickness and reduced cost of quality.

The reduced cost of quality far exceeds the additional alloy cost for the Nb addition. The MicroNiobium Approach in these higher carbon steels has been implemented on an industrial scale for 1050 sheet steels in the automotive fastener industry. A 30-day time period was selected to introduce MicroNb alloy additions in the range of 0.010-0.020%Nb in all AISI 1050 steel industrial heats. No change was made in the melting, reheating furnace or hot rolling mechanical or process metallurgy practices. [10] The performance assessment executed an Activity-Based Cost (ABC) comparison methodology which measures the tonne per hour hot rolling production rate, the percent of diverts for flatness, shape and mechanical properties and the cobble scrap rate for the MicroNb heats versus the historical non-Nb heats' performance. This ABC methodology is highly recommended for all MicroNb medium and high carbon experimental validation and justification. ABC has proven to be highly effective in terms of gaining an accurate understanding of the cost reduction, implementation time and quality impact.

In the comparison of the MicroNb to the non-Nb historical performance, the steel operation experienced a minimization of abnormal austenite grain growth which translated into a finer ferrite grain microstructure. The measured improvement parameters directly attributed to the Nb, as that was the only change made in the process were:

1. Improved processability and rollability at the mill
2. Reduced cobble rate
3. Reduced diverts for poor quality
4. Increased production rate (i.e. tonne per hour)
5. Reduced mechanical property variability

These attributes resulted in an approximate 3-5% reduction in operational cost per tonne and a lower Total Activity Based cost of production for the MicroNb 1050 steel compared to the non-Nb 1050 steel grade. The Industrial 1050 MicroNb Automotive Sheet Implementation Methodology described is a case study for global research and operational metallurgical community to analyze the cost-benefit of the Nb-pinning effect for medium and high carbon steels. The critical success factor is that no change in heating or rolling practices (such as reduction schedules, discharge temperature, roughing, finishing and coiling temperatures were made. Each mill performs their respective metallurgical and operational analysis.

8 CONCLUSIONS

High reheat furnace temperatures (exceeding 1225°C) reduce the impact toughness and DWTT performance due to inhomogeneous heating and a coarse prior austenite grain size through the slab thickness. The proper heating temperature, time and reduction schedule is the key in optimization of the finest grain size leading to DWTT consistently exceeding 85% shear fracture even at the plate centerline. The variability in toughness from the ¼ to ½ point of the plate can be attributed to improper furnace heating. The operational furnace parameters such as AFT, air-to-gas ratio, O_2 in the furnace atmosphere are operational contributors to poor toughness. The introduction of micro-additions of Nb assists in the production of a more robust hot rolled product retards austenite grain growth caused by reheat furnace process temperature and time irregularities.

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