Reheat Furnace Operational Effect on Hot Roll Product Quality

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INTRODUCTION

The reheating process has a profound effect on the final hot rolled steel quality and mechanical property consistency. The uniformity of heating applied across the entire width and length of the slab or billet is critical in the achievement of 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. There are numerous reheat furnace process metallurgy and combustion parameters in the actual operation that affect mill productivity, scrap rate and diverts. This reheating step in the steelmaking process often receives low priority in the evaluation of product quality and mechanical property performance, especially the toughness through the plate thickness. In laboratory studies, the furnace heating step is typically quite uniform resulting in a homogeneous and fine prior austenite grain size. Unfortunately, in industrial operations, it is much more difficult to control the uniformity of heating along the entire length and through the thickness of the work piece. This factor is often not given high priority when evaluating mechanical property diversions on an industrial scale. The furnace conditions are correlated to product quality via furnace process variables such as the air to gas ratio, furnace burner condition, furnace pressure, energy efficiency, adiabatic flame temperature (AFT) and furnace refractory condition. Corrective actions and operational practice recommendations are presented in order to minimize inhomogeneous heating which results in inferior product quality and toughness variations in the through-thickness-direction.

BACKGROUND INFORMATION

The performance and efficiency of the reheating process affects the austenite grain size and its uniformity of grain size along the entire length and through thickness of the slab. Improper reheat and soak zone temperatures and times are a root cause of mechanical property variations in the final product. There has been extensive study and research in the process metallurgy of the steelmaking and secondary ladle metallurgy, hot rolling, recrystallization, mechanical metallurgy and deformation reduction schedules, and cold finishing. However, often the thermodynamics and kinetics during the reheat and soak steps of the process receive low priority in the evaluation of product quality and mechanical property performance. The heating performance directly influences the final hot rolled product microstructure and final grain size. Several combustion and operational variables affect the heating and soaking of the steel slabs or billets in the reheat furnace. For example, the homogeneity and efficiency of heating is highly influenced by the air-to-gas ratio of the furnace burner combustion condition. The optimization and consistency of the stoichiometric air-to-gas ratio should be one of the top operational priorities in the hot roll process. Simultaneously, the goal is achievement and maintenance of the highest possible AFT. A consistently high AFT translates into minimization of the prior austenite grain size and inhomogeneity. Variable AFT corresponds with variable heat input into the steel and correspondingly variable austenite grain size. This mechanism of abnormal and variable grain growth has been well established and documented on a laboratory scale. [1] However, as is often the case, translating this laboratory data to actual industrial furnace conditions is quite cumbersome and inaccurate. Consequently, this relationship between reheat furnace operational conditions and slab temperatures, as well as its effect on prior austenite grain size and the final effect on mechanical properties, such as through thickness toughness, yield to tensile ratio, stretch flangeability, etc. and associated data scatter, are rarely reported on an industrial scale. Industrial samples, grain size determination and processing data should be evaluated and correlated accordingly. A second important consideration involves the thermodynamic and kinetic aspects of the laboratory furnace conditions versus the full scale industrial furnace conditions.

Two examples of this discrepancy between laboratory and industrial conditions involve the predicted austenite grain size and the solubility of different alloying elements at different carbon contents. The traditional approach from the research-side is to maximize the solubility of a given microalloying element, such as niobium (Nb) in carbon steels to ensure the alloy's effectiveness in grain refinement, recrystallization kinetics and subsequent precipitation, especially in low carbon steels. Maximization of solubility is extremely important, but experience has shown that if at least 70-80% of a microalloy enters into solution, desired recrystallization and predicted fine grain size is achieved. Industrial reheat furnace experience exhibits a positive effect for a microalloy such as Nb via the formation of undissolved NbC or Nb(C, N) precipitates which will assist in the pinning of the prior austenite grain boundaries. [2] Regardless of the microalloy of choice, a significant variation in AFT causes inhomogeneous heat input thereby resulting in a variable prior austenite grain size (PAGS). This inhomogeneity of heating becomes the root cause for variations in the final hot rolled microstructure, grain size and mechanical properties, especially toughness. Hence, since such inconsistencies in furnace heating are often ignored in research studies, many researchers incorrectly assume and conclude that the composition or role of a given microalloy is the problem if poor mechanical property performance is experienced, when in fact the furnace heating practice is the root cause. Furnace heating practice relates; 1) reheat top and bottom zone set points, 2) soak zone temperature set point, 3) actual reheat top and bottom zone and soak zone temperature, 3) times in each zone related to push rate, 4) furnace pressure, 5) combustion air flow, 6) air-to-gas ratio and 7) overall refractory and furnace maintenance.

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 (Figure 1) 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.

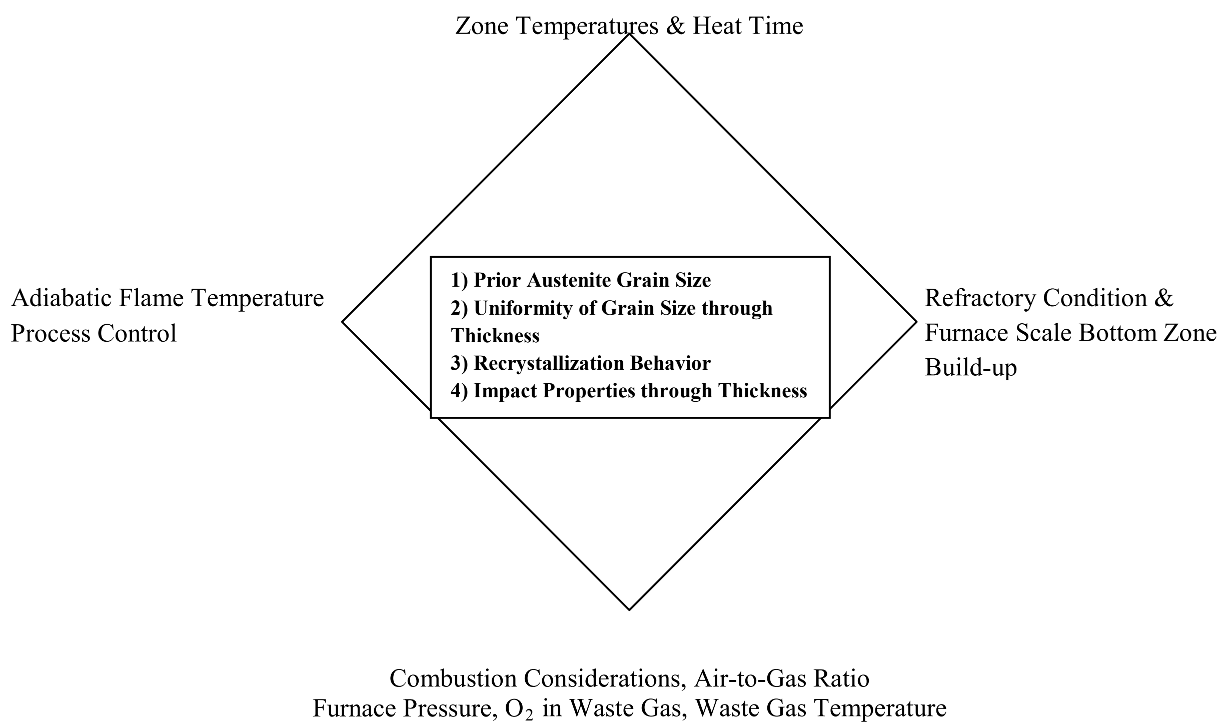


Figure 1. Furnace process control variables, prior austenite grain size and properties

COMBUSTION CONSIDERATIONS

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 influences the deformation schedule, recrystallization and 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 AFT is affected by the fuel type, burner efficiency and air to gas equivalence ratio. The highest adiabatic flame temperature 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 2 illustrates the effect of different air-to-gas ratios (i.e. equivalence ratios) on the adiabatic flame temperature for different gases.

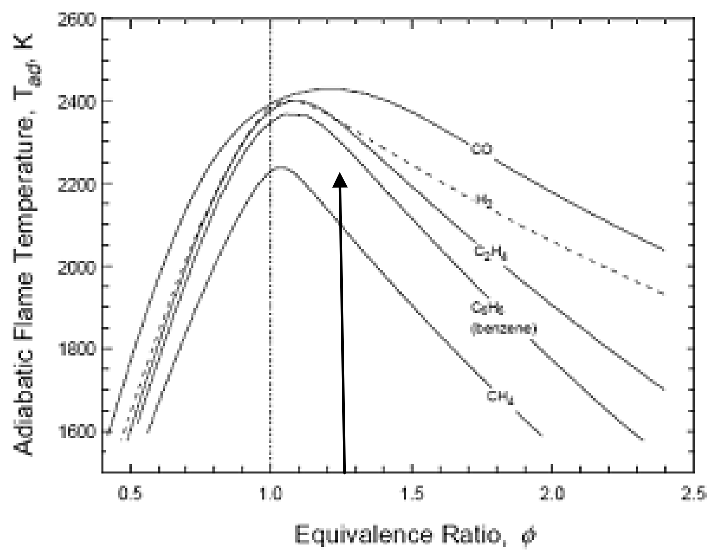


Figure 2. Air to gas equivalence ratio versus adiabatic flame temperature

Since most furnaces consume natural gas, the maximum adiabatic flame temperature of 2250°K occurs at approximately 1.10 equivalence ratio. Under these conditions, approximately one-half of the heat generated from the combustion of the fuel heats the steel. As the equivalence ratio increases, combustion efficiency declines and AFT decreases. There are several operational reasons that adversely increase the equivalence ratio. [3] The following furnace factors can create higher equivalence ratios:

- 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

Numerous furnace operations throughout the world operate at both high reheat (>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. Figure 3 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.

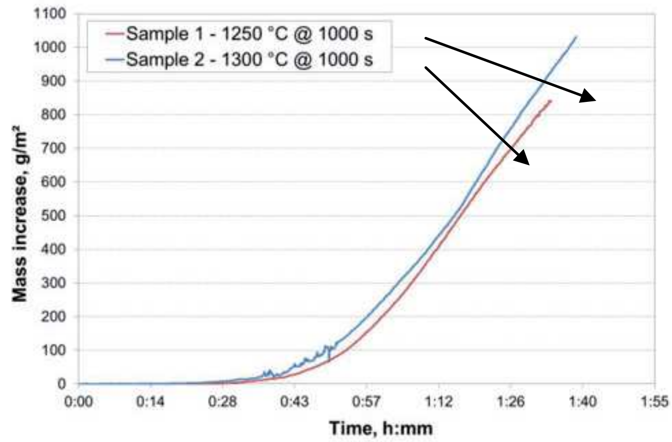
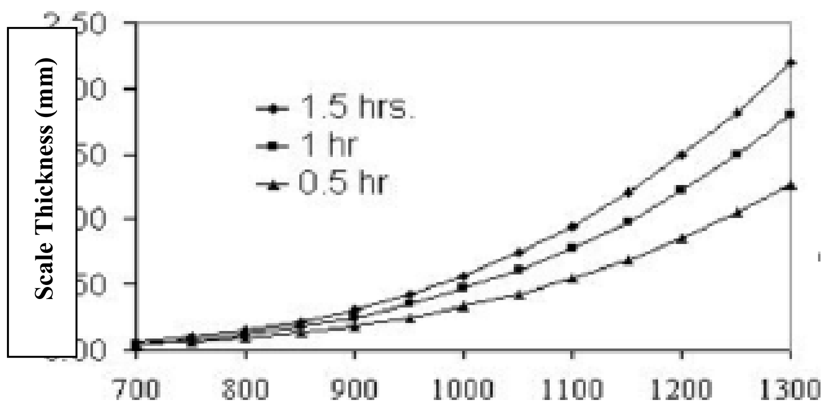


Figure 3. Increase in mass over time for oxidation at 1250° and 1300°C in methane combustion atmosphere [4]

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 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 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. This loss in product translates into millions of dollars of scrap on an annual basis. The relationship between furnace temperature and scale thickness is illustrated below in Figure 4.



Temperature (°C) 0.49.pdf

Figure 4. Scale thickness versus temperature [5]

It is apparent from Figure 4 at 1200°C, an increase in hold time from 1.00 to 1.50 hours will increase the scale thickness by nearly 30%. Scale behaves as an insulator and consequently, the thicker the scale then a reduction in the thermal conductance of heat absorbed by a given slab is reduced. A second factor involves the influence of the air-to-gas ratio. As the air-to-gas ratio decreases, the AFT decreases and then due to more oxygen in the furnace environment, the iron oxide scale thickness will increase. 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 properties, the 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. The scale that is formed has the right properties for simple and effective scale-breaking and removal prior to rolling or forging operations. [6] In some cases, it is possible to reduce or eliminate some downstream processing as well. One customer reports that the surface properties improved so much with oxyfuel their skin-pass operation could be eliminated. [7]

The reheat furnace process metallurgy 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 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). Variable austenite grain size often occurs in actual production for a variety of reasons. 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. However, they are often ignored and no adjustments are made.

EFFECT OF REHEAT PROCESS ON MECHANICAL PROPERTIES

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 difference 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.

Table 1. Impact toughness variations through plate thickness

Nb-Grade	**Location**	**-80°C**	**-60°C**	**-40°C**	**-20°C**	**0°C**	**20°C**
Q550	Surface	145	175	205	225	230	240
Q690	Surface	75	155	215	220	230	235
Q550	1/4	140	175	190	230	250	248
Q690	1/4	115	200	220	225	250	252
Q550	1/2	30	180	175	190	210	210
Q690	1/2	25	105	150	205	245	215

Figure 5 compares the microstructures at the surface, quarter-point and centerline of the 48mm plate noting the microstructural and grain size differences for the surface, ¼-point and centerline of the plate.

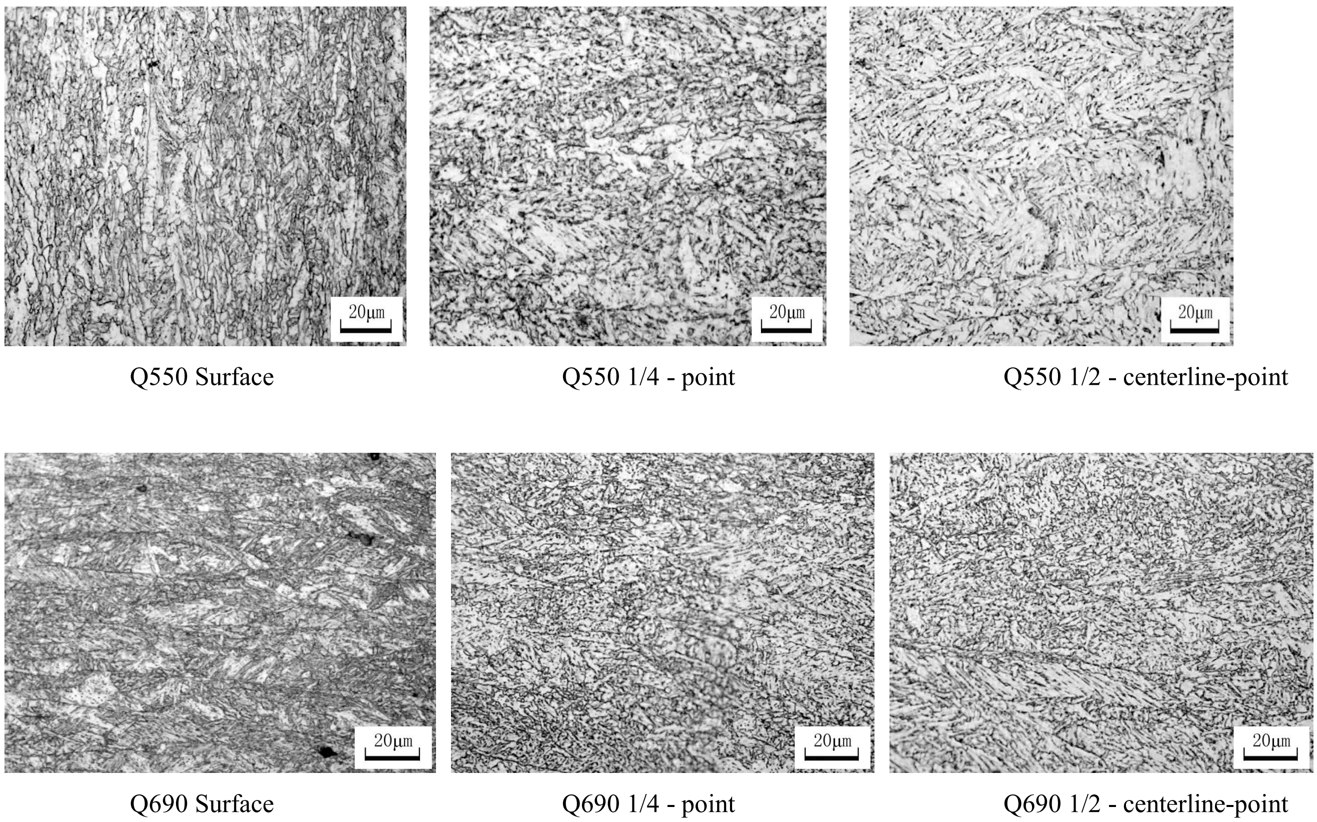


Figure 5. Microstructure at surface, ¼ and ½ point in plate thickness

MICROALLOY EFFECT DURING REHEAT PROCESS

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 6 below illustrates the cuboidal shape of the TiN precipitates and the spherical 3-5nanometer NbC precipitates attached to the TiN precipitate.

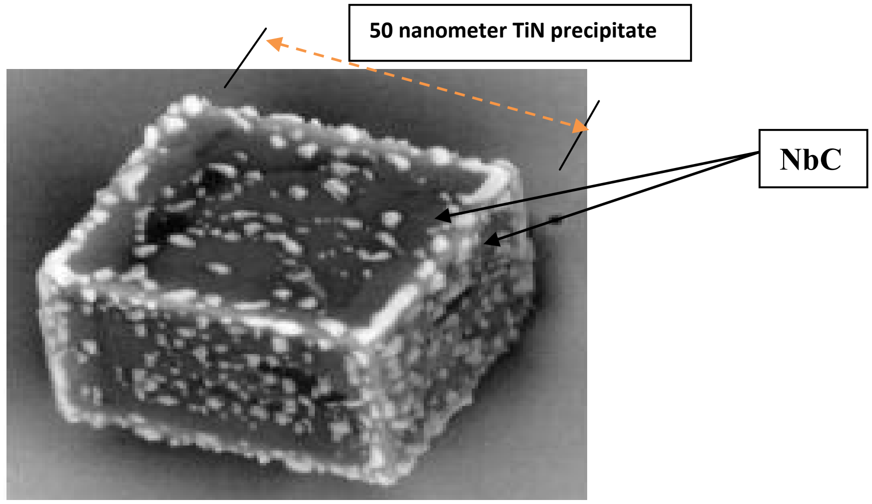


Figure 6. 50 nm cuboidal titanium nitride precipitate with spherical NbC epitaxial precipitation

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 [8] 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 7).

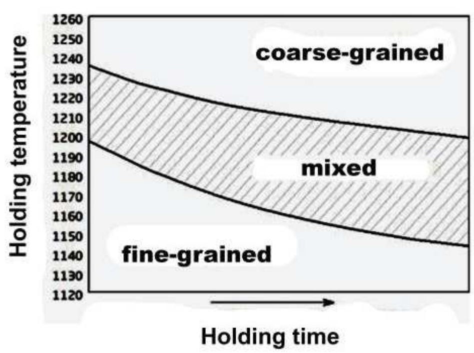


Figure 7. Structural conditions of austenite in microalloyed steels after reheating [9]

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 [9], 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 7.

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-meter hot rolling mill of Vyksa Steel Works in Russia. [8] 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 imposed 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 this 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 (Figures 8 and 9.) [8]

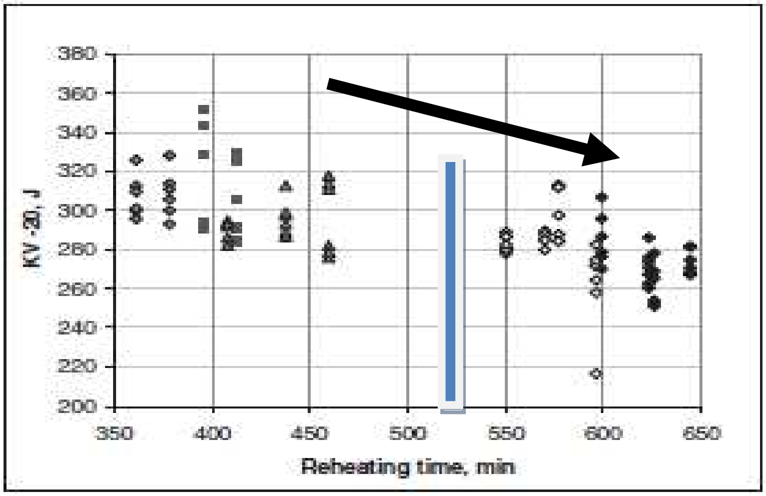
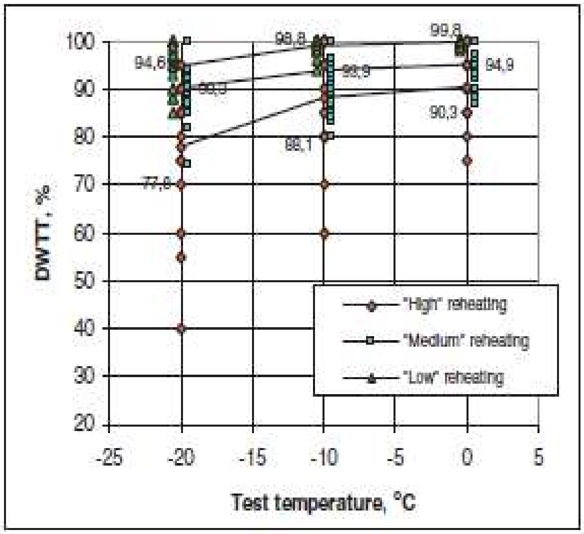


Figure 8. KV-20°C - J as function of time at 1170°C [8]

Figure 8 above 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. Close evaluation exhibits less scatter in toughness data for a given heating time at reheating less than 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. This recrystallization phenomena is 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 reheating. Preservation of fine-grained austenite microstructure after reheating does not eliminate the possibility of grain refinement during TMCP. Development of optimal deformation schedules can provide additional microstructure refinement. Increase of reduction per pass does not always allow desirable refinement of austenite grain during rolling of thick plates. This force/torque limitation of rolling mills should be considered. The important issue is uneven deformation across the slab cross-section during roughing. Outer layers are being conditioned better than the inner ones. Furthermore, there is temperature gradient between the slab surface and inner layers. Higher temperature of the slab core promotes a higher rate of grain growth after static recrystallization (SRX). A long pause time between roughing and finishing also contributes to the growth of recrystallized austenite grain in order to provide the required finishing rolling temperature (FRT). The percent ductile shear deteriorates as the reheat temperature increases and the finishing rolling stage is often started below Ar3. An accelerated cooling of thick plates, especially in the middle of the cross-section, is performed at a limited cooling rate, so the possibilities for refining microstructure components are limited. [10]

The blend of the 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 %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 9.



High reheat = 1260°C
Medium reheat = 1190°C
Low reheat = 1160°C

Figure 9. Shear area of DWTT vs. DWTT test temperature [8]

There is more scatter from 40% to 95% DWTT (at -20°C test temperature) for the high reheat soak zone temperatures compared to the medium and lower holding temperatures with scatter from 75% to 100% DWTT at -20°C test temperature..

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. Figure 10 schematically outlines the industrial relevance and cost-benefit considerations to justify the industrial trials.

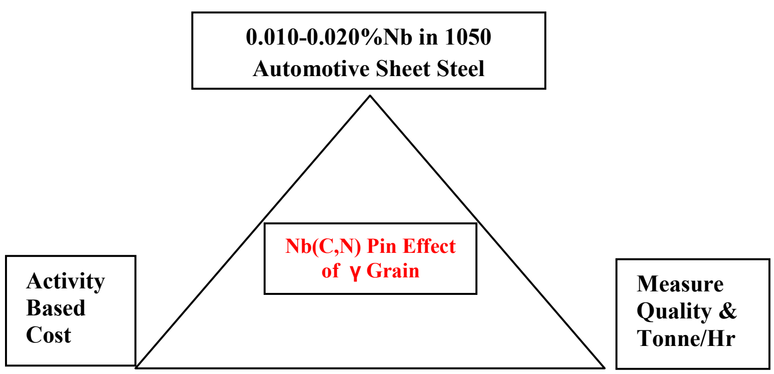


Figure 10. Industrial 1050 MicroNb automotive sheet implementation methodology [3]

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. 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. Since the %Nb levels are so low, the recrystallization mechanism is just initiating (≤5%) or not even measurable in these higher carbon grades. Thus, no change in reduction schedules is necessary making this development quite easy to implement into operations.

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 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 product as it retards austenite grain growth due to reheat furnace temperature and time irregularities.

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