

REHEAT FURNACE OPERATIONAL PARAMETERS AFFECTING HOT ROLL QUALITY OF MICROALLOYED LONG PRODUCTS

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Abstract

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 or billet. The resultant ferrite grain size in the final hot rolled product is significantly governed by the initial prior austenite grain size (PAGS). This reheating step in the steelmaking process often receives low priority in the evaluation of product quality and mechanical property performance. In laboratory studies, the furnace heating step is typically quite uniform resulting in a homogeneous and fine PAGS. 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. Such inhomogeneity and efficiency of heating is highly influenced by several combustion process variables such as the air to gas ratio, furnace burner condition, furnace pressure and refractory 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. These situations have a huge effect on the optimal adiabatic flame temperature performance which translates into inhomogeneous austenite grain size and variations in mechanical properties in the hot rolled product. Corrective actions and operational practice recommendations to minimize inhomogeneous heating effects on product quality are presented.

Keywords: adiabatic flame temperature, air-to-gas ratio, combustion, quality, solubility

1. INTRODUCTION

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. However, the heating performance directly influences the final hot rolled product microstructure. Several combustions 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 optimum air to gas ratio of 1.10 yields the highest adiabatic flame temperature. Effectively, variable adiabatic flame temperature means variations in the heat input to the steel and the austenite grain size. The mechanism of abnormal grain growth is well established and documented. [1] However, the relationship between reheat furnace operational conditions and temperatures and its effect on prior austenite grain size and final effect on mechanical properties and scatter is rarely reported. Also, the austenite grain size predictions and solubility of different alloying elements at variable carbon contents in actual industrial operations is difficult to correlate with laboratory studies and generated data. For example, the traditional approach has been 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. However, fundamentally, regardless of the microalloy, a variable adiabatic flame temperature means variations in the heat input resulting in a variable prior austenite grain size. This inhomogeneity of heating becomes the root cause for variations in the final hot rolled microstructure, grain size and mechanical properties. These inconsistencies often lead to incorrect



conclusions during the product development stage of composition design and predicted mechanical property performance. 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 between combustion effectiveness, metallurgy and its effect on austenite grain size is emphasized with the objective of improving quality and mechanical property consistency.

2. DISCUSSION

2.1 Adiabatic Flame Temperature and Reheat Furnace Combustion Considerations

Variable adiabatic flame temperature means variations in the heat input to the steel and the austenite grain size. Figure 1 illustrates the effect of variations in the air-to-gas ratio (i.e. equivalence ratio) on the adiabatic flame temperature for different gases.



Fig. 1 Air to Gas Equivalence Ratio versus Adiabatic Flame Temperature

The highest adiabatic flame temperature translates into higher 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, which acts as an insulating layer on the slab surface, reducing the slab heat conduction efficiency. Under these conditions, longer soaking times will ensure proper heating of the center of the slab. 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. [2]

Periodic checking and resetting of air-fuel ratios for burners is one of the simplest ways to get maximum efficiency out of fuel-fired process heating equipment such as furnaces, ovens, heaters, and boilers. Most high temperature direct-fired furnaces, radiant tubes, and boilers operate with about 10% to 20% excess combustion air at high fire to prevent the formation of dangerous carbon monoxide and soot deposits on heat transfer surfaces and inside radiant tubes. For the fuels most commonly used by U.S. industry, including natural gas, propane, and fuel oils, approximately one cubic foot of air is required to release about 100 British thermal units (Btu) in complete combustion. Exact amount of air required for complete combustion of commonly used fuels can be obtained from the information published in combustion references. However, the condition of the furnace and its burners must be assessed to properly utilize this data. Process heating efficiency is reduced considerably if the combustion air supply is significantly higher or lower than the theoretically required



air. If the actual air is higher than theoretical air for stoichiometric combustion, the equivalence ratio exceeds 1.10. The quality implications are increased iron oxide scale thickness, reduced thermal conduction, longer soak times and ineffective heating at the center thickness of the work piece. Root cause issues for high equivalence ratios relate to infiltration of air into the furnace, cracked refractories, poor sealing furnace and inspection doors and cracked burner orifice plates. [2]

The converse effect of a low equivalence ratio means the furnace is burning rich and wasting fuel, thereby creating excess carbon emissions and lower adiabatic flame temperatures. The effect on product quality is inhomogeneous heating, ineffective microalloy dissolution into the austenite, cold steel and poor finishing and coiling temperature performance resulting in inconsistent mechanical properties.

2.2 Reheat Furnace Temperature Effect on Austenite Grain Size

The translation from adiabatic flame temperature to reheat furnace temperature is quite complex, especially in actual operations where the furnace condition and local heat loss conditions must be taken into account. When conditions of overheating or underheating exist, discontinuous austenitic grain growth can occur. Discontinuous austenite grain growth is directly influenced by thermal variation conditions within the furnace caused by variables such as air to gas ratios, refractory conditional heat loss and furnace pressure. 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 2). [3] The connection between the process metallurgy and the physical metallurgy is made.



Fig. 2 Austenite Grain Size vs. Reheating Temperature [3]

The methodology presented here is the relationship between the air to gas ratio and the resultant austenite grain size which can be correlated with the integration of these two figures (Figure 1 and Figure 2). 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, at 60 minute heating time, if one section of the slab is at 1225°C and the adjacent section is 1200°C due to an air to gas variation of 0.05; then it follows that the austenite grain size would be approximately 500µm for the 1225°C section versus the adjacent section at 400µm grain size for the 1200°C region. This 100µm differences in prior austenite grain size is due to the temperature differences on the slab due to unequal local heating along the slab length. The premise follows that the 100µm difference in prior austenite grain size in the final hot rolled product and hence, variable mechanical properties. The relationship between variable final ferrite size and mechanical property scatter is well established.



2.3 Ramifications of Large and Variable Prior Austenite Grain Size in Final Hot Rolled Product

The proper conditioning of the hot rolled austenite prior to transformation is necessary to ensure the appropriate microstructure and composition to allow the desired final ferrite microstructure to be formed after transformation. High rates of ferrite nucleation will result from having a very large number of potential nucleation sites and a high nucleation rate per site. These sites for ferrite nucleation include grain boundaries, incoherent twin boundaries and deformation bands. It then follows that if there is variation in the PAGS, then the ferrite nucleation process will yield ferrite grain sizes of different diameter. The preferred nucleation and growth of proeutectoid phases and pearlite at austenite grain boundaries establishes a direct relationship between the austenite grain size and final grain size of the transformation products. Fundamentally, the finer the austenite grain size then the higher the probability that final grain size of the product will be smaller. It is important to differentiate between the two different types of austenite transformation of: (a) reconstructive transformation, which is a diffusion controlled process that takes place at a higher temperature and (b) displacive transformation which is diffusionless in nature and occurs at low temperatures. The products of the first reconstructive transformation are ferrite and pearlite whereas bainite and martensite forms through the displacive mechanism. When the microstructure becomes unstable, a few grains may grow excessively, consuming the smaller recrystallized grains. This process, which may lead to grain diameters of several millimeters or greater, is known as abnormal grain growth or secondary recrystallization. The driving force for abnormal grain growth is usually the reduction in grain boundary energy as for normal grain growth. Abnormal grain growth can only occur when grain growth is inhibited.

A second factor often ignored in actual operation is the heating rate of the slabs or blooms before hot rolling. Operational delays due to maintenance issues, quality problems or roll changes can result in longer soak times. Increased PAGS may occur if the furnace temperatures are not reduced during the delay as depicted in Figure 2. Conversely, if the furnace temperatures are reduced during the delay, operators often rapidly ramp up the furnace burners after the delay, hence increasing the heating rate, in the interest of productivity. The heating rate of the work piece in the furnace influences the prior austenite grain size. Figure 3 illustrates this relationship of the average grain size at different soaking temperatures and heating rates for extremely short heating times. [4] The relative differences in grain size should be noted instead of the absolute grain size in this illustration.



Fig. 3 Average Prior Austenite Grain Size at Soaking Temperature and Different Heating Rates



The actual heating rate in most industrial billet and slab reheat furnaces are typically between 5 to 10°C/sec and fall between the upper curves of Figure 3. As the heating rate increases, the average PAGS decreases. It is recommended that future PAGS research studies evaluate the grain size distribution instead of the average PAGS and report accordingly. A few large austenite grains in a fine grain matrix create microstructural deviations and mechanical property scatter. For example, the problems in most industrial furnaces with high heating rates (exceeding 10 to 20°C/sec), result in slabs that are often not homogeneously heated through the thickness. This thermal profile condition will result in a variable PAGS through the thickness and mixed variable grains in the final product. Mechanical property ramifications in this case result in poor impact toughness at the ¼-point and centerline of the hot rolled bar or plate.

3. RESULTS

3.1 Influence of Grain Size Variation and Mechanical Property Scatter

A variety of mechanical properties may be affected by the austenite grain size and PAGS size distribution. Such affected properties may involve strength, ductility, toughness, hardness, fracture appearance transition temperature, z-direction toughness, fatigue and stress-strain behavior during inelastic deformation. The relation between austenite grain size and mechanical properties has been examined by many researchers. Among them Zhao et.al [5] studied that the mechanical properties of a low-carbon micro alloyed cast steel may be enhanced by controlled heat treatment. They determined that correct selection of the austenitizing temperature, holding time and cooling method is very important to improve the mechanical properties. However, the PAGS originally created via the slab reheat furnace process before hot rolling will have an influence on these post hot roll treatment microstructures. Also, in some cases, post heat treatment or normalizing heat treatments in plate steel products may be completely eliminated if PAGS control practices are implemented. [6]

The boundaries of fine austenite grains will be the preferred sites for pearlite nucleation. Moreover, the austenite to pearlite transformation rate increases with a decrease of austenite grain size due to an increase in nucleation rate of pearlite. These microstructural features influence mechanical properties. Figure 4a and b relates PAGS for to FATT and yield strength for a 25CrMo48V steel where the carbon is 0.25%.[7]



Kaijalainena et al. [8] investigated the effect of the prior austenite grain structure on the microstructure and properties of two low carbon and low alloyed hot rolled and direct quenched martensitic steels.



Fig. 5 Prior austenite grain size and T28J for low carbon and low alloyed martensitic steels.

Industrially, an increase in the rolling reduction in the non-recrystallization temperature regime of austenite is an effective way to improve the strength, impact and fracture toughness without a significant decrease in uniform elongation. In addition, the finer the PAGS exiting the reheat furnace prior to hot rolling reduction at temperature, then the more consistent will be the resultant microstructure, grain size and mechanical properties.

3.2 Solute Pinning of Prior Austenite Grain Boundary in Industrial Operations

Solute additions, such as Nb, Ti and/or V, demonstrate different degrees of effectiveness in pinning the prior austenite grain in industrial operations. At temperatures below the grain coarsening temperature, the pinning force exerted by the particles is sufficient to prevent grain coarsening through secondary recrystallization or abnormal grain growth. The influence of various microalloying elements on prior austenite grain coarsening during reheating under laboratory conditions is shown in Figure 8. The hatched region below represents the relative comparison of the coarsening temperature region for each type of steel.



Fig 8. Austenite Grain Growth Behavior vs. Reheating Temperature for Low Carbon Steels [9]

However, more recent research data has shown the grain coarsening behavior of Nb-containing steels to be suppressed to temperatures as high as 1230°C. [10] It is important for laboratory conditions to emulate actual industrial furnace heating profiles and heating rates.



4. CONCLUSIONS

The consistency of the reheat furnace operation and the uniformity of heating along the entire length and through thickness of the work piece will affect prior austenite grain size. The overall thermal efficiency is highly dependent upon several combustion process variables such as the air to gas ratio, furnace burner condition, furnace pressure and refractory condition. For example, the optimum air to gas ratio of 1.10 yields the highest adiabatic flame temperature and most efficient heating condition. Since time at temperature conditions govern the PAGS, variable austenite grain size will directly influence several mechanical properties such as yield strength, ductility and fracture arrest temperature toughness,

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