Effect of Carbon Content on the Grain Refinement of Locally Produced Plain Carbon Steel by Thermal Cycling

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Abstract: In this work the effect of carbon content on grain refinement in carbon steels was investigated. Grain refinement achievable in carbon steels through thermal cycling was studied by subjecting carbon steels with four different carbon levels (0.1%C, 0.39%C, 0.81%C and 1.04%C) to thermal cycling at an austenitizing temperature of 880°C, and an intercritical temperature of 740°C for 2, 4 and 6 cycles. The results showed that grain size decreased with increasing number of thermal cycle up to the fourth cycle after which further cycling did not produce any observable grain refinement but grain coarsening. Grain size reduction was more pronounced the higher the carbon content for samples A (0.1%C) and D (0.39%C), while for samples N (0.81%C), and P (1.04%C) the reduction is less pronounced the higher the carbon content

Key words: grain size, grain refinement, thermal cycle, carbon content, carbon steel

INTRODUCTION

The attainment of finer ferrite grain structure in carbon steel is of interest because significantly higher yield strength and lower ductile-brittle transition temperatures can be achieved at the same time with ultra-fine grain sizes\(^1\). The properties of various types of steel and of any given steel alloy at varying temperatures depend primarily on the amount of carbon present\(^2\), and how it is distributed in the iron. Refining of the final grain size of steels is one of the biggest challenges in order to produce high strength steels with improved toughness and ductility. Grain size is one of the microstructural features, which influence the properties and response of metals to heat treatment more than others. This is particularly true for steel because the grain size, be it austenite or ferrite, influences not only the yield and tensile strengths, but also the ductility, ductile-brittle transition temperature, creep strength, and high-temperature ductility. Also, the austenite grain size affects the transformation characteristics of steel and through them the hardenability of the steel. It is therefore no exaggeration to state that control of the grain size enables the control of the whole response of steel to heat treatment, and the consequent mechanical properties.

Traditionally, grain size control in an alloy is obtained by the addition of grain growth inhibitors such as aluminum, titanium, zirconium and vanadium. The fine grain thus obtained promotes a low ductile-to-brittle transition temperature, tends to reduce the hardenability of the steel, but does not significantly affect the strength of the steel. A relatively new and more efficient technique for grain refining is the thermal cycling. The method consists of repeated cycles of rapid cooling from the austenite and the two-phase (\(\alpha+\gamma\)) range. It utilizes the fact that an austenite grain transforms to several ferrite grains on cooling whereas a single ferrite grain transforms into many austenite grains on heating. The method produces better grain refinement in steels\(^3\). The steels become ultra fine grained and hence exhibit increased strength and toughness. According to Pan\(^4\), by repeating the low temperature reheating cycle (thermal cycle) to refine prior grain size, an ultra fine ferritic grain can be obtained in steel.

2.0 Experimental Procedure: The chemical composition (wt %) of the steel samples investigated is given in Table 1. The samples were provided by the local industry after hot rolling.

The austenitizing temperature \(A_C\), that defines the ferrite + austenite (\(\alpha+\gamma\)) region was determined by Andrew’s \(^5\) empirical formula, as shown in equation 1.

\[
A_C = 723 - 10.7Mn + 29.1Si + 16.9Cr - 16.9N + 12.90As + 6.38N
\]  

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This temperature was found to be 723.99°C for sample A. Therefore the inter-critical treatment was performed at 740°C while the austenitizing treatments were performed at 880°C. For each thermal cycle, the samples were soaked at the austenitizing temperature for 5 minutes, quenched in water at room temperature, and then re-heated to the inter-critical temperature without soaking and then quenched in water. The process was repeated for 2, 4 and 6 cycles. Specimens were prepared for microscopy following standard technique and 2% Nital was used as etchant. The microstructural examination was carried out on an Olympus Metallurgical microscope at a magnification of 100x. The grain size was measured by Jefferies planimetric method, as shown in equation 2

\[
N_A = \frac{M^3 (n_1 + n_2)}{5000} \quad (2)
\]

M = Magnification of photographic image.
\(n_1\) = number of grains completely in the inscribed area
\(n_2\) = number of grains intersecting the perimeter of the test area
The ASTM grain size number was then computed from equation 3

\[
A = [3.322 \log N_A] - 2.95 \quad (3)
\]

RESULT AND DISCUSSION

3.1 Effect of Carbon Content on Grain Size: Figure 1 shows the effect of carbon content on grain size. It was observed that for a given number of austenitizing cycles the average grain size decreased with increased carbon content for the hypo eutectoid samples with sample D (0.39%) having the greatest refinement after four cycles. Grain size reduction observed for A (0.1%) and D (0.395%) C is probably due to the fact that cycling increases the number of very fine carbide particles which inhibit grain growth. It could also be due to the fact that increase in carbon content decreases the austenite to ferrite transformation temperature and so causes refinement. Carbon also increases the hardenability of steel and so facilitates the formation of martensite during cooling from the austenite phase, and thus the finer the grain size obtained from higher carbon content. However for samples N (0.81% C), and P (1.4% C), the reduction was less pronounced the higher the carbon content. This is probably due to higher growth tendencies the higher the carbon content. The effect of carbon content however diminished with increasing number of austenitizing cycle beyond four cycles. Also observed was the effect of carbon content on the number of cycles required before the minimum grain size was obtained. Fewer number of cycles is required the higher the carbon content.

3.2 Effect of Carbon Content on Mechanical Properties: Figure 2 shows the ultimate tensile strength of the steel sample after various number of thermal cycles. The Figure shows that the ultimate tensile strength increased with increasing number of thermal cycles up to the fourth cycle after which further cycling did not produce any observable increase in strength. This change is consistent with the changes in grain size. Strengthening in Fe-C is a combination of solute strengthening and a refinement in grain size. The strength of martensite increases proportionally to the square root of the carbon content. For samples A and C, where carbon content is less than or approximately equal to 0.2%wt, increase in strength is probably due to carbide precipitation while in samples N and P, the increase in strength is obtained in the as-quenched, martensitic condition i.e. solute strengthening is greater than that obtained by carbide precipitation.

3.3 Effect of Carbon Content on Microstructure: Figures 3-6 show the microstructure of the various steel samples in the as-received form and after thermal cycling. It was observed that the grain size was slightly smaller the higher the carbon content. It was generally observed that the microstructures became finer with increasing number of cycles with the first few austenitization cycles producing microstructures with uneven grain size distribution and finer structures with a good degree of homogeneity after further cycling.

Higher proportion of ferrite was observed with increase in the carbon content. This is because martensite increases with increase in the carbon content. The higher the carbon contents of the steel, the higher the carbon content of the austenite and the higher the tendency of martensite formation. The
Fig. 1: Effect of carbon content on grain size at 880°C
Fig. 2: Ultimate tensile strength at 880°C
Fig. 3: Optical photomicrograph of the steel samples before heat treatment. Light areas are ferrite grains and dark areas the pearlite phase. 
Etchant: 2% Nital  
X 100

Fig. 4: Optical photomicrograph of the steel samples after 2 cycles of thermal cycling treatment at 880°C and 740°C with intermediate water quenching. Light areas are ferrite grains and dark areas are pearlite phase. 
Etchant: 2% Nital  
X 100
Fig. 5: Optical photomicrograph of the steel samples after 4 cycles of alternate thermal cycling heat treatment at 880°C and 740°C with intermediate water quenching. Light areas are ferrite grains and dark areas are pearlite phase. Etchant: 2% Nital X 100

Fig. 6: Optical photomicrograph of the steel samples after 6 cycles of alternate thermal cycling heat treatment at 880°C and 740°C with intermediate water quenching. Light areas are ferrite grains and dark areas are pearlite phase. Etchant: 2% Nital X 100
diffusion of carbon from the carbon enriched constituents into the austenite at the austenitizing temperature is time dependent and the homogenization of carbon composition may not be possible in a single cycle for short holding time. The higher the carbon content of the steel samples, the higher the carbon composition of the austenite and the higher the proportion of martensite formed after quenching. As shown in these Figures, unequal grain size distribution was observed and this is suspected to be as a result of undissolved proeutectoid ferrite in the two-phase region, which remained after quenching.

Conclusion: Thermal cycling produced appreciable grain refinements in the carbon steels. Cycling beyond four cycles did not provide noticeable additional grain refinement but rather lead to improved uniform grain size distribution. Grain size reduction was more pronounced the higher the carbon content for samples A (0.1%C) and D (0.39%C), while for samples N (0.81%C) and P (1.04%C), the reduction is less pronounced the higher the carbon content.

REFERENCES