Prediction of austenite grain growth during austenitization of a 0.7%C pearlitic rail steel

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Abstract

The prior austenite grain size of steels greatly influences the phase transformation kinetics during austenitization and the microstructure which determines the mechanical properties. The effect of temperature and time on austenite grain growth of 0.7% carbon rail steel during reheating was studied. The grain growth behaviour of this steel was investigated under different heating temperatures and holding times at a constant heating rate of 4°C/min. Samples were heated in a tube furnace at temperatures of 1150, 1200 and 1250°C and held for 0, 1800, 3600, 5400, 7200 and 9000 seconds before quenching into water. The prior austenite grains were observed using an optical microscope and austenite grain sizes were measured by the linear intercept method. The measured austenite grain sizes were used in determining the grain growth constants Q, A and n which were used in developing the constitutive equation for grain growth prediction. A good agreement was found between the actual and the predicted austenite grain size within the typical industrial soaking temperature range of 1150 and 1200°C.

The constitutive equation was found to be $D^{4.5} = [6\,x10^{19} \exp(-\frac{355\,x10^3}{RT})t\,]$

Keywords: Microstructure, grain growth, austenite, pearlite, temperature, time

1. Introduction

Pearlitic steels are widely used for railway rails due to their high yield strength, good fatigue strength, good wear resistance and excellent weldability (Beynon and Perez-unzueta 1993).

During the manufacturing process, the steels are austenitized and soaked for a specific period. The soaking temperature and time are the primary controlling variables in the austenitization process, as the starting grain structure influences the final grain structure and the properties entailed by the steel (Duan, et al., 2010). These two parameters also affect the grain growth behaviour through the dissolution and distribution of precipitates. The austenitizing temperature and time, control the prior austenite grain size, austenite recrystallization, refinement and phase transformation in the steel during reheating and on cooling (Sha and Sun, 2009). The pearlite structure, which provides strength to this type of steel results from eutectoid decomposition of austenite through growth of ferrite and cementite lamellae. The production process of pearlitic steels therefore entails careful consideration of the chemical composition and process conditions that will lead to the formation of pearlite structure. It is worthy to note that the mechanical properties of steels greatly depend on the fraction of phases produced following the thermomechanical processing conditions. High yield strength, wear resistance and high hardness are some of the properties required for rail application steels and they are achieved through careful control of the grain structure and size during processing. Very high austenitizing temperatures and long holding times may result in grain growth, distortion and loss of metal strength

(Porter, et al., 1992). It has been pointed out that temperature and time greatly influence austenite grain growth and eventually the mechanical properties of the steels, with temperature being the most effective parameter (Annan, et al., 2015; Lee and Lee 2008; Zhang et al. 2011). Due to the difficulty and limitations posed by in-situ measurement of grain size during heat treatments, to monitor grain growth behaviour, it has become ideal to study the grain growth behaviour of steels through the use of constitutive prediction equations. The kinetics of grain growth in metals have been widely studied, especially for low carbon micro alloyed steels, looking at the effects of various alloying elements, and many models specific to those steels that have been developed (Annan, et al, 2018; Zhang et al. 2011). The control of austenite grain growth in medium to high carbon steels have focused largely on the impact of chemical composition on grain structure control. The objective of the current work is to study the effects of austenitizing temperature and time on the grain growth of 0.7% C rail steel through the development of a constitutive equation to predict the grain behaviour during austenitization.

2. Material and experimental procedure

The material used in the current study is C–Mn, grade R260 rail steel. The chemical composition of the studied steel is shown in Table 1.

In order to obtain the effect of austenitizing temperature and holding time on the austenite grain growth, square samples of 10 mm x10 mm x 5 mm were heated in a vertical tube furnace

Table 1: Chemical composition of the R260 rail steel used in the study, in mass %

C	Mn	Si	P	S	Cr	Al	V	Ni	N
0.73	1.17	0.32	0.015	0.01	0.04	0.001	0.025	0.01	0.008

at temperatures of 1150, 1200 and 1250°C using a heating rate of 4°C/min and held for times of 0, 1800, 3600, 5400, 7200 and 9000 seconds before being subsequently quenched into water at room temperature. Figure 1 shows the schematic thermal profile of the heat treatment used. The austenitizing temperatures and times used in this investigation are comparable to typical conditions used in the rail manufacturing plants. Quenched specimens were metallographically prepared and etched with Picral to reveal prior austenite grain structures. The austenite grain structures were observed using an *Olympus* optical microscope and grain sizes were measured using linear intercept method with the help of *Image J* software. Average grain size measurements were done on 3 to 4 representative areas from each sample at 100x magnification as recommended in ASTM E112.
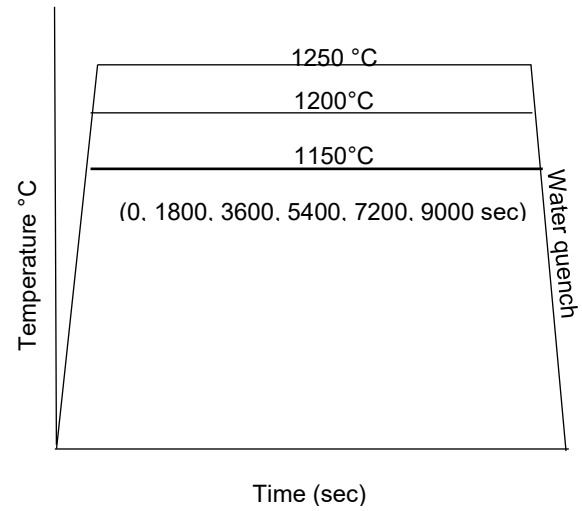

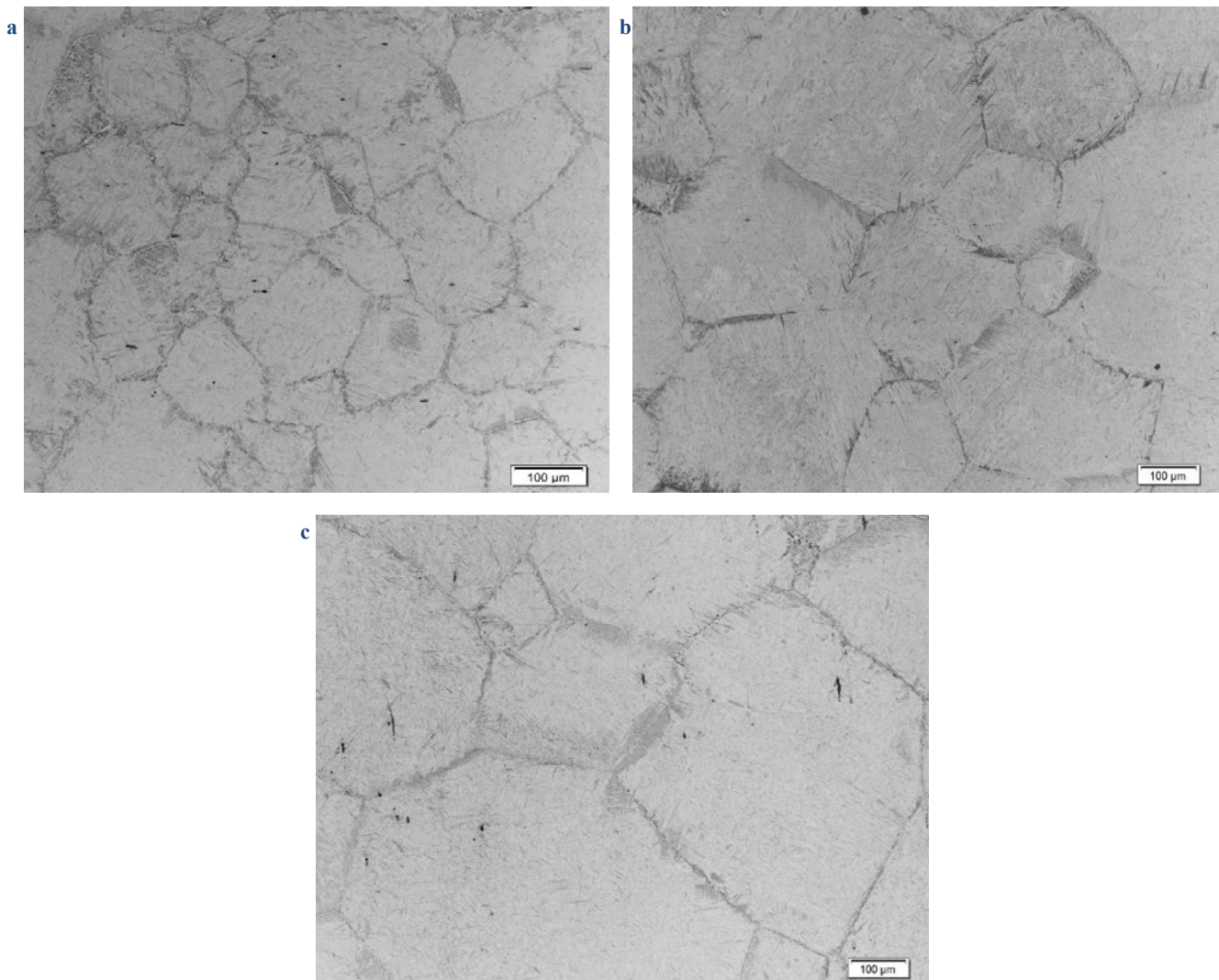**Figure 1:** Schematic diagram of the heat treatment profile used in the study

Figure 2: Optical micrographs of steel heat treated for 3600s and austenitizing temperatures of (a) 1150ºC (b) 1200 ºC (c) 1250 ºC. All images taken at 100x magnification
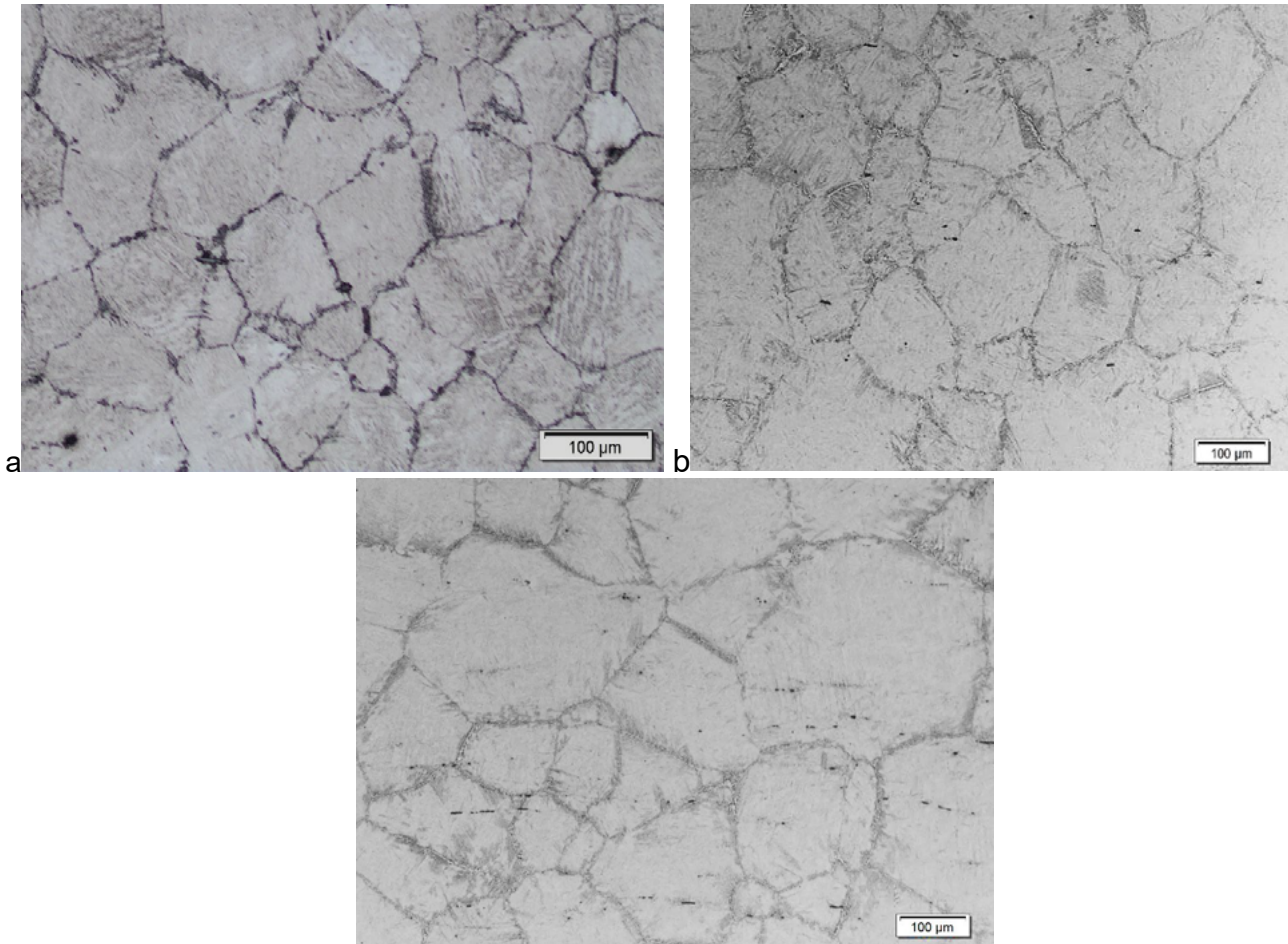
Figure 3: Optical micrographs of steel heat treated at 1150 for a). 1800s b). 3600s and c). 7200s all images taken at 100x magnification

3.   Results and Discussion

3.1   Microstructural analysis

Figure 2 shows the optical micrographs of the steel samples heat treated at the different austenitizing temperatures and held at the same soaking time. It is visually, observed from these images that there is an increase of grain size as the austenitizing temperature increased. At temperatures 1200 and 1250˚C in Figures 2(a) and (b) abnormal grain growth is observed, in a form of unequal grain sizes distribution (Hodgson and Gibbs, 1992).

Figure 3, presents the micrographs of steel samples heat treated at the same austenitizing temperature but held for different soaking times. There is an observation of increased grain size with increased holding times. The observed increased grain size with increase in temperature and time is comparable to results reported by many authors (Annan, et al, 2018, Hodgson and Gibbs, 1992, Zhang, et al, 2011). It is understood that at 1200ºC and above, the carbides which are effective in pinning grain boundaries, to control the grain growth, have all dissolved and therefore leading to a rapid increase in grain growth.
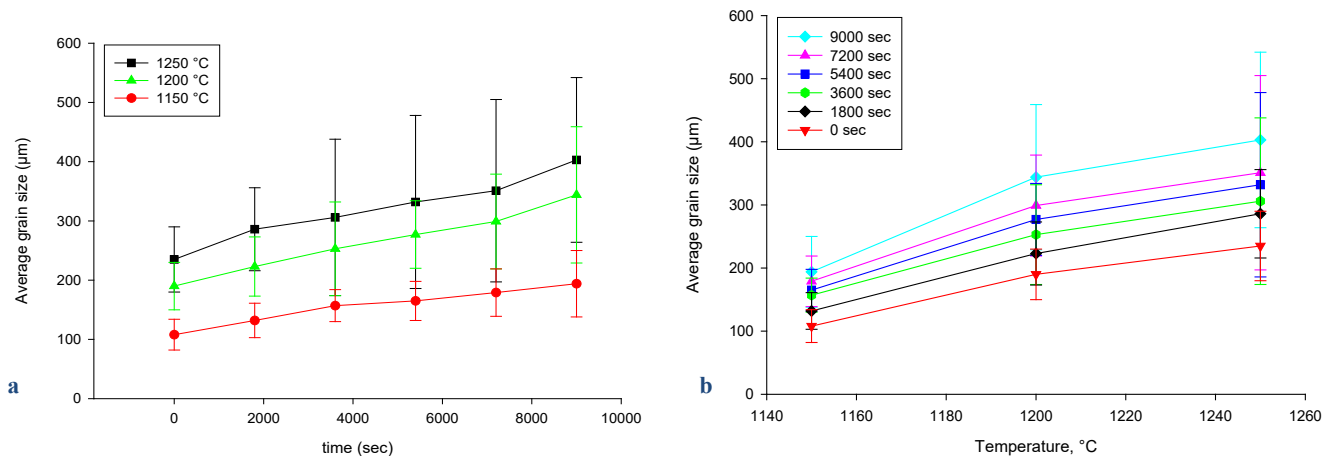

Figure 4: Isothermal grain growth behaviour of austenite in steels showing an increase in grain size with a) time and b) temperature

3.2 Effect of time and temperature on austenite grain size

Quantitative analysis of the experimentally measured austenite grain sizes as a function of temperature and time is shown in Figure 4. The graphs evidently display the influence of time and temperature on grain growth in the steel with temperature proven to be more effective than time.

3.3 The development of a constitutive equation using the constants n, Q and A

The Arrhenius type constitutive equation developed by Whiteman and Sellars, 1979 used to study austenite grain growth under isothermal conditions, shown in Equation 1, was used in the current study.

$$D^n - D_o^n = At \, \exp\left(-\frac{Q}{RT}\right) \qquad \text{Eqn. 1}$$

Where D is the mean grain size, D_o is the initial grain size, n is the grain growth exponent, A is a material constant, t is time, Q is the activation energy for grain growth, R is the gas constant (8.314 J/mol/k), and T is temperature in Kelvin.

Considering that $D >> D_o$ and that $D_o \approx 0$, Equation 1 can be re-written as Equation 2:

$$D = \left[A t \exp\left(-\frac{Q}{RT}\right) t\right]^{1/n} \qquad \text{Eqn. 2}$$

By taking natural logs (ln) on both sides of Equation 2, Equation 3 is obtained. When a plot of ln D versus ln t is constructed, the slope of the graph is $1/n$ (see Figure 5) and the value of the grain growth exponent n can thus be determined as follows:

$$\frac{1}{n} = \frac{\partial \ln D}{\partial \ln t} \text{ with T kept constant} \qquad \text{Eqn. 3}$$

From the grain growth empirical Equation 4
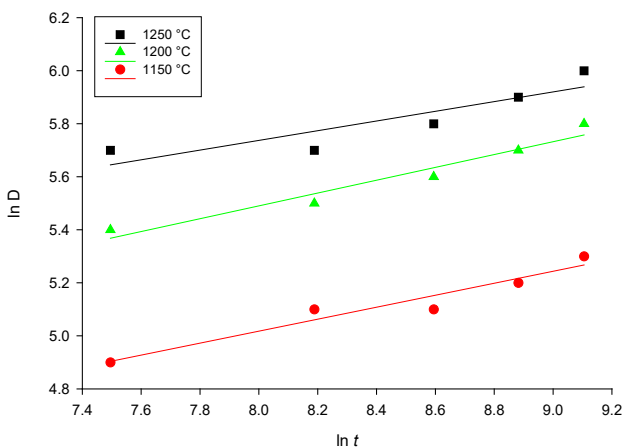
$$D^n = Kt \qquad \text{Eqn. 4}$$

Figure 5: The plot of ln D as a function of ln t

Making K the subject of Equation. 4, implies;

$$K = \frac{D^n}{t} \qquad \text{Eqn. 5}$$

From Equation 5, the value of K was calculated for different temperatures and times using the measured D values and the n determined from Figure 5.

From Equation 1, K is a temperature dependant constant given by;

$$K = K_o \exp\left(\frac{-Q}{RT}\right) \qquad \text{Eqn. 6}$$

Taking natural logs to base 10 (ln) on both sides of Equation 6, using two variables K_1 and K_2, Equations 7 and 8 were constructed.

$$lnK_1 = \frac{-Q}{RT_1} + \ln A_1 \qquad \text{Eqn. 7}$$

$$lnK_2 = \frac{-Q}{RT_2} + \ln A_2 \qquad \text{Eqn. 8}$$

Since A is a material constant, $A_1 = A_2 = A$, therefore subtracting Equation 7 from Equation 8;

$$\ln\left(\frac{K_2}{K_1}\right) = \frac{Q}{R}\left(\frac{Q}{RT_1} - \frac{Q}{RT_2}\right) \qquad \text{Eqn. 9}$$

Hence, with K_1 and K_2 determined at temperature T_1 and T_2, Q was calculated using Equation 10;

$$Q = \frac{\ln\left(\frac{K_2}{K_1}\right) R}{\left(\frac{1}{T_1} - \frac{1}{T_2}\right)} \qquad \text{Eqn. 10}$$

Then from, Equation 1 when $D_o=0$);

$$D^n = A \exp\left(\frac{-Q}{RT}\right) t$$

hence, A was determined using Equation 11 as:

$$A = \frac{D^n}{\exp\left(\frac{-Q}{RT}\right) t} \qquad \text{Eqn. 11}$$

The constants n, A and Q generated from the current study in comparison with existing values in the literature are presented in Table 2.

Table 2: Comparable austenite grain growth constants

Author	n	Q (kJ/mol)	A
Yue, et al., 2009	0.36	458	3.12×10^{19}
Chamanfar, et al., 2020	0.20	230	4.2×10^{16}
Current study	0.22	355	6×10^{19}

The generated constants were used in developing the constitutive Equation 12.

$$D^{4.5} = \left[6 \times 10^{19} \exp\left(-\frac{355 \times 10^3}{RT}\right) t\right] \qquad \text{Eqn. 12}$$

Figure 7, shows the plot of predicted austenite grain size against measured grain size over the tested temperature ranges using the
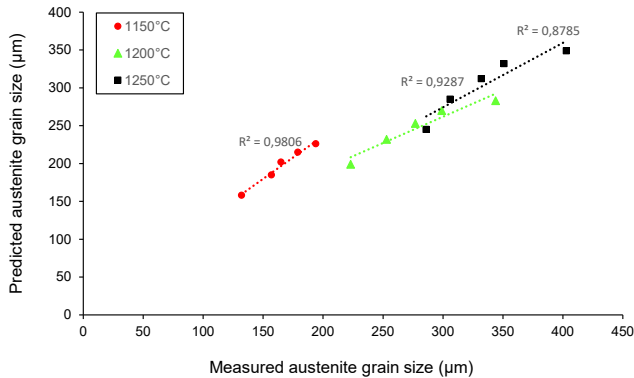
Figure 7: Comparison of predicted and experimental grain growth behaviour in the steels

constitutive equation developed in the current work. The figure indicates a very good prediction capability of the developed constitutive equation for 1150˚C and 1200˚C, with co-efficient of determination of 0.98 and 0.93 respectively.

4. Conclusion

In the present study, the effect of temperature and time on austenite grain growth behaviour was studied. Based on results and analysis done, the conclusions below are drawn:

1. Grain growth in the 0.7%C steel studied, was found to increase with increasing temperature and time. Temperature was however found to be more effective in increasing grain size than time.

2. The grain growth constants n, Q and A were found to be 0.22, 355 KJ/mol and 6 x 10^{19} respectively.

3. The constitutive equation developed for predicting grain size of this studied steel with a temperature range of 1150ºC – 1200ºC is

$$D^{4.5} = \left[6\,x10^{19}\,\exp\left(-\frac{355\,x10^3}{RT}\right)t\right]$$

4. The prediction capability of the current developed constitutive equation is found to be very good as compared with the measured values of grain sizes.

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6. Author Contribution

Experimentation, formal analysis, writing up: S. Khanyema
Writing up, analysis and review: Kofi A. Annan

Conceptualization, funding acquisition, analysis and review: R Mostert

Project administration, review – C.W. Siyasiya

Funding acquisition, review: Joseph Moema

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