

Austenite-Bainite Transformation Kinetics in Austempered AISI 5160 Steel

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Abstract

This research investigates the process of the formation of bainite in austempered 5160 steel. Steel bar samples were austenitized at 1128 K for 20 minutes followed by holding at various times from 10 seconds to 2 hours and isothermal temperatures from 561K to 728K to obtain a multi-phase matrix. Micro-hardness analysis and metallurgical optical microscopy were used to analyze the experimental results. Hardness results indicated that at the 561K, 589K, and 566K isothermal temperatures for 5160 steel, lower bainite transformation occurred. However, from 644K to 728K, upper bainite transformation was found from the steel. The formation of the bainitic phase in SAE 5160 steel was characterized using thermodynamic and kinetic theories.

Keywords: Material Science, formation of bainite, 5160 steel, isothermal temperatures

Introduction

SAE 5160 steel is a high carbon and chromium spring steel, which is commonly used by forgers. It has excellent toughness, outstanding ductility, high yield to tensile strength ratio, and a high level of shock resistance which make it a suitable spring steel for parts exposed to stress, vibration, and shock. SAE 5160 is used in the automotive field in applications, such as scrapers, equalizers, bumpers, and various heavy spring applications, especially for leaf

springs. Since it has good impact resistance, it is also used for knives that need to hold an edge. To enhance the properties of 5160 steel, heat treatment processes are commonly used (Krishna et. al., 2013) such as austenitizing and austempering to produce bainite.

The bainite transformation has been investigated for several decades (Speer et. al., 2004, Grajcar et. al., 2014, Borgenstam et. al., 2012, Durand-Charre, 2004, Bhadeshia, 1990, Bhadeshia et. al., 1980, Lawrynowicz, 2016, Takahashi, 2004) Generally, the process of bainite isothermal transformation is composed of two steps (Lawrynowicz, 2016, Soliman et. al., 2016, Zhou et. al., 2017): austenitizing and austempering. In the austenitizing step, steel is heated above the critical temperature and held until the austenite transformation is complete. For the austempering step, bainite is formed by an isothermal heat treatment and obtained from the decomposition of austenite, this process is called austempering (Krauss, 1990, Navarro-Lopez et. al., 2017). Martensite is typically also contained in the microstructure which is obtained from the residual austenite (Junior et. al., 2013).

Bainite is a non-lamellar mixture of ferrite and carbide. Due to the difference of carbide precipitates, it can be classified into upper bainite and lower bainite (Bhadeshia, 1992, Caballero et. al., 2004, Quidort et. al., 2001). Both are aggregates of small plates or laths of ferrite. The ferrite in upper bainite is free of precipitates. Carbide particles precipitate from the supersaturated bainitic ferrite for the lower bainite formation (Bhadeshia, 1992). There are several types of steel and cast iron for which the bainite transformation has been studied (Tomita et. al., 1993, Khan et. al., 1990, Saeidi et. al., 2009, Johnson et. al., 1993), however, the bainite transformations of 5160 steel from austenite at various austempering temperatures and times have not been fully investigated. Thus, this investigation is focused on a study of the process of the bainite transformation from austenite in austempered 5160 steel. The bainite transformation kinetics are discussed as well.

Experimental Procedure

Material

The chemical composition of the 5160 steel is presented in Table 1. Rockwell hardness measurements were done and it was found that the as-received 5160 steel hardness is 24 HRC.

Table 1: The chemical composition of 5160 steel (wt. %)

C	Cr	Fe	Mn	P	Si	S
0.56-0.64	0.7-0.9	97.085-97.84	0.75-1.0	≤0.035	0.15-0.3	≤0.04

Heat Treatment

All the samples were cut into half disks with a diameter of 3cm and a

thickness of 0.7cm, Figure 1 shows the original microstructure of the specimens before heat treatment. It can be seen that the microstructure is primarily pearlite.

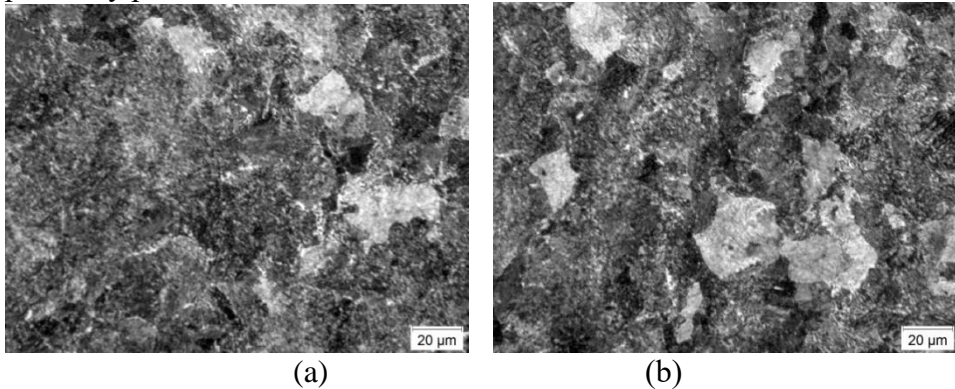


Fig.1 Microstructure of original specimen material: a) Longitudinal Section (500X), b) Transverse Section (500X).

To study the 5160 steel bainite transformation process, all the specimens were first austenitized and then austempered. The specimens were austenitized at 1128K for 20 minutes, and then held at various austempering temperatures and different times. Seven different austempering temperatures of 561K, 589K, 617K, 644K, 672K, 700K, and 728K were utilized and holding times were 10s, 15s, 20s, 30s, 40s, 45s, 50s, 60s, 3mins, 5mins, 10mins, 15mins, 30mins, 1hour, and 2 hours, respectively. The heat treatment process is shown in Figure 2. After finishing the two heat treatment steps, samples were removed from the salt bath and water quenched to room temperature. The high and low temperature furnaces are shown in Figure 3.

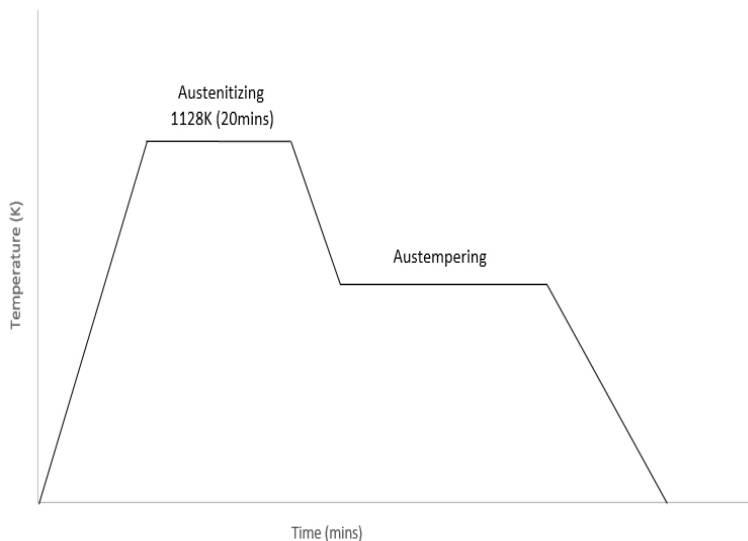


Fig.2 Heat Treatment Process

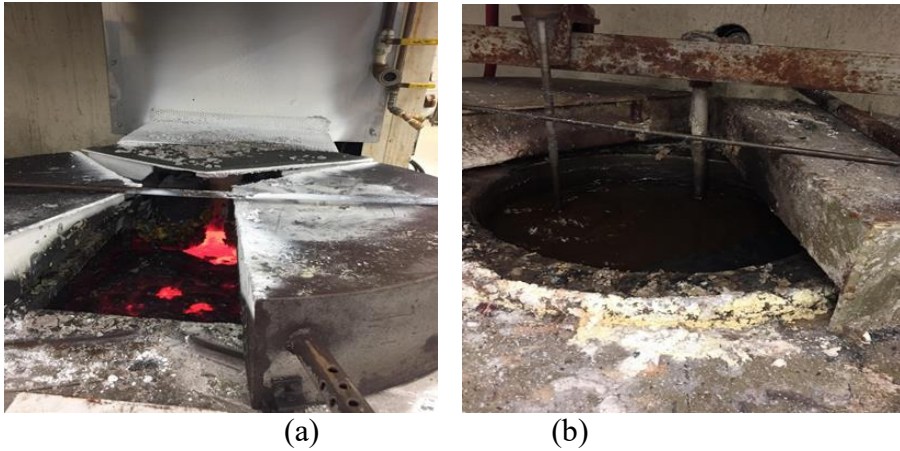
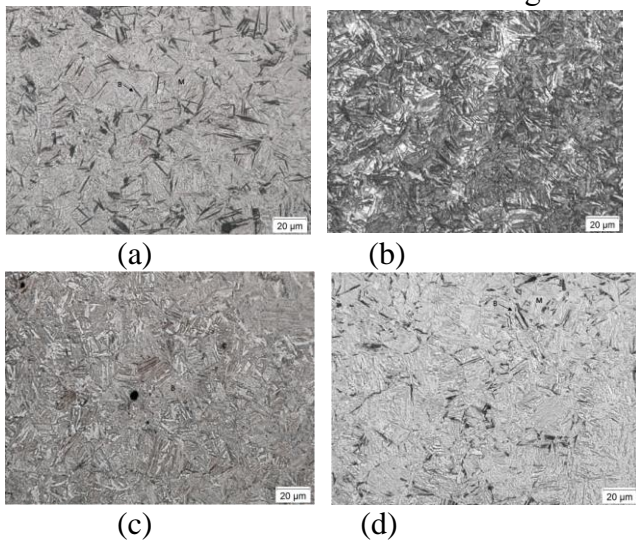


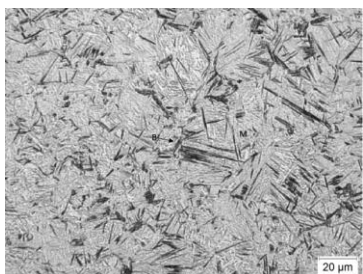
Fig. 3 Salt Bath Furnaces: a) High Temperature, b) Low Temperature

Results

Microstructure of austempered 5160 steel

The microstructures of the austempered specimens of 5160 steel austempered from 561K to 728K with various times are shown in Figure 4. All the austempering times and temperatures produced at least some bainite microstructure. The needle like structure (bainite) increases as the austempering time is increased. Bainite transformation is observed at three levels: beginning, medium, and finish. Since the upper bainite microstructure is coarser than lower bainite, it was observed that lower bainite is produced from 561K to 617K, however, 672K to 728K produced upper bainite. Upper bainite and a small amount of lower bainite were observed at 644K. The fraction of martensite decreases with longer holding times.

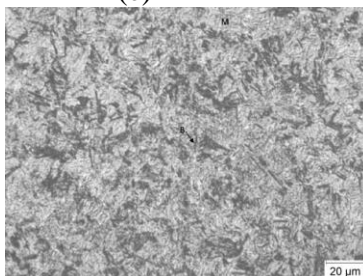




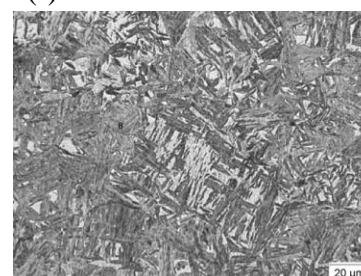
(e)



(f)



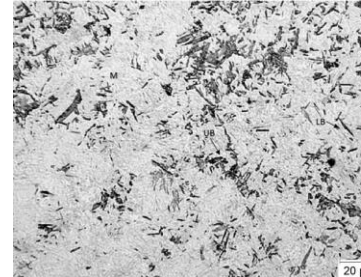
(g)



(h)



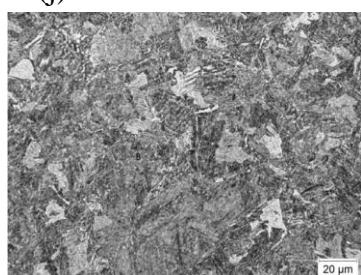
(i)



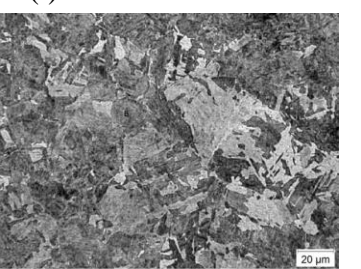
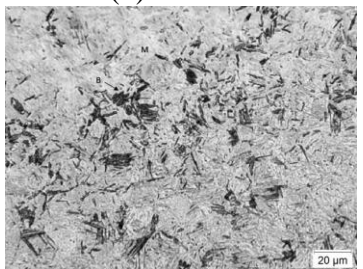
(j)



(k)



(l)



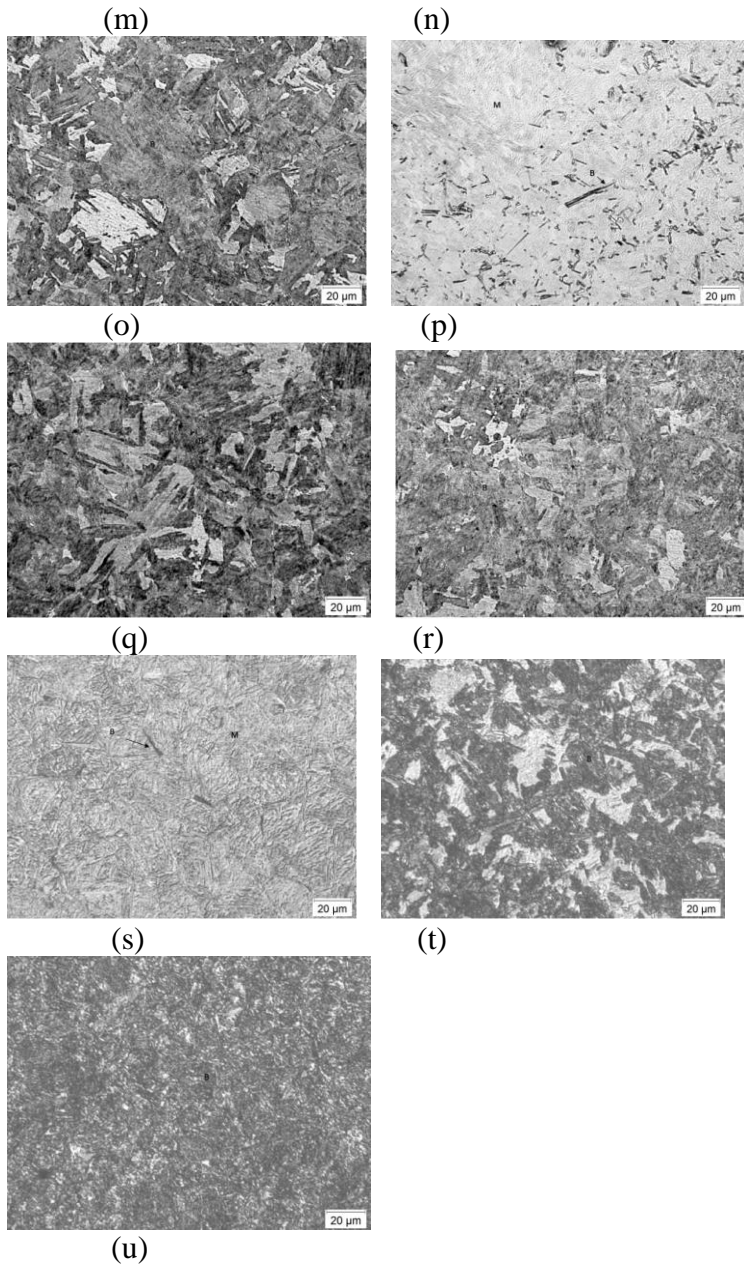
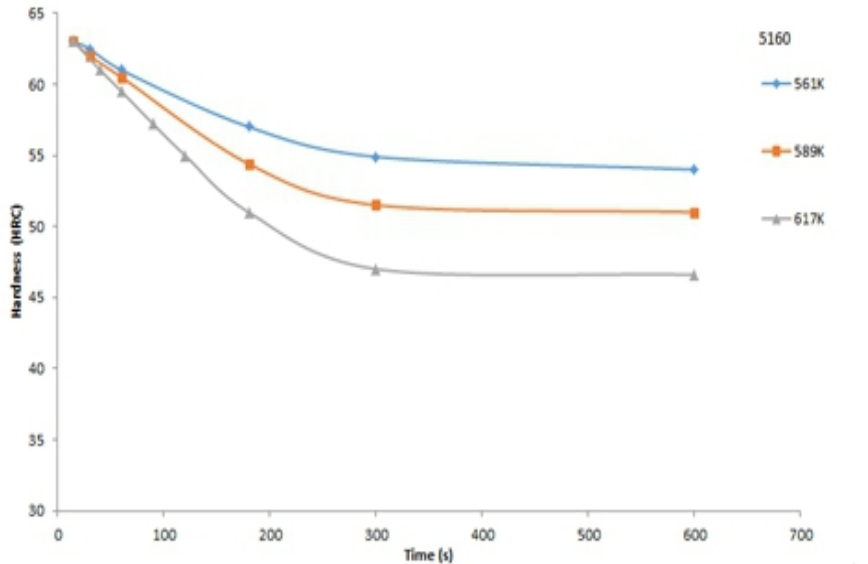


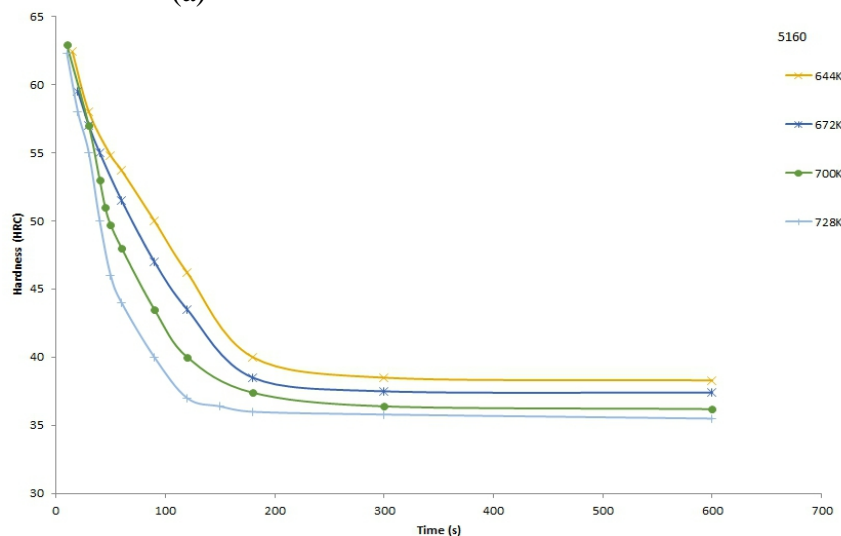
Fig. 4 Microstructure of 5160 steel at different temperatures with various austempering holding time: a) 561K - 3mins, b) 561K -15mins, c)561K - 120mins, d) 589K-30s, e) 589K – 60s, f) 589K – 120mins, g) 617K – 30s, h) 617K – 30mins, i) 617K – 120mins, j) 644K – 30s, k) 644K-3mins, l) 644K-120mins, m) 672K - 20s, n) 672K – 3mins, o) 672K – 120mins, p) 700K – 10s, q) 700K- 3mins, r) 700K – 120mins, s) 728K – 10s, t) 728K – 60s, u) 728K- 120mins

Hardness (HRC) Measurements

Hardness was measured three times for each sample. The average hardness values are presented in Figure 5. Figure 5.a shows hardness with specimens containing lower bainite. Figure 5.b shows hardness of samples containing upper bainite from 672K to 728K, 644K shows primarily upper bainite with a small amount of lower bainite. It can be seen that as the austempering temperature and holding time increase, all the hardness values decreased.



(a)



(b)

Fig.5 5160 material hardness obtaining with different austempering temperature and holding time: a) 561K, 589K, 617K, b) 644K, 672K, 700K, 728K

Transformation Kinetics

The bainite transformation kinetics was studied using hardness analysis. It utilized the following function (Milosan, 2008, Ioan, 2014):

$$X(t) = \frac{H_0 - H(t)}{H_0 - H_f} \times 100\% \tag{1}$$

Where: $X(t)$ – The fraction of transformation;

H_0 – The initial hardness, which corresponds with the first bainite transformation beginning after a specific holding time;

$H(t)$ – The hardness obtained after a holding time at the austempering temperature;

H_f – The final hardness which corresponds with the last transformation of the bainitic reaction.

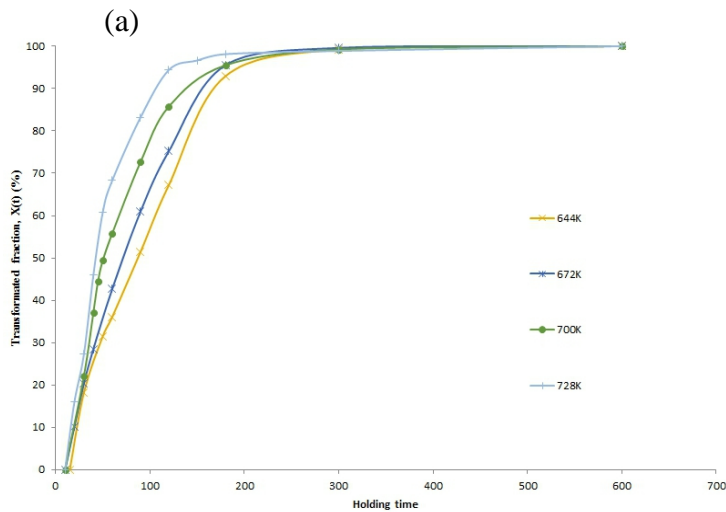
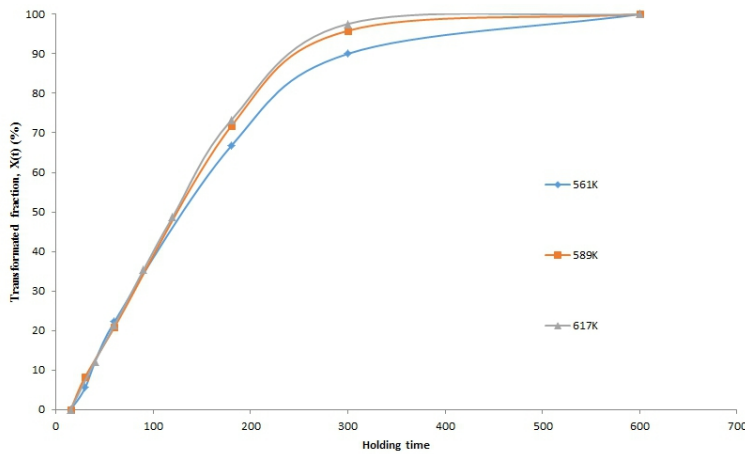


Fig.6 5160 Transformation Fraction: a) comparison among 561K, 589K, and 617K, b) comparison among 644K, 672K, 700K, and 728K

Figure 6 shows the bainite transformation fraction at different austempering temperatures. When comparing 561K, 589K, and 617K, as the temperature increases for the same holding time, higher temperature results in faster transformation. Austempering temperatures of 644K, 672K, 700K, and 728K show a similar trend.

The “Avrami” equation is used to describe the relationship between the transformed fraction and different temperature at various times. The equation is as follows (Milosan, 2008, Ioan, 2014, Umemoto et. al., 1982, Bhadeshia, 1982):

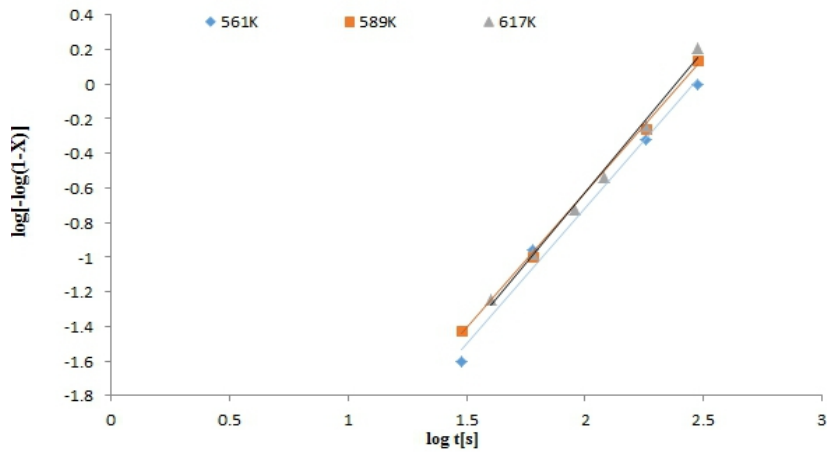
$$X(t) = 1 - \exp(-k t^n) \tag{2}$$

Where: $X(t)$ - Transformation fraction at a certain time
 k – Rate constant which depends on temperature
 n - Slope of “Avrami” plot

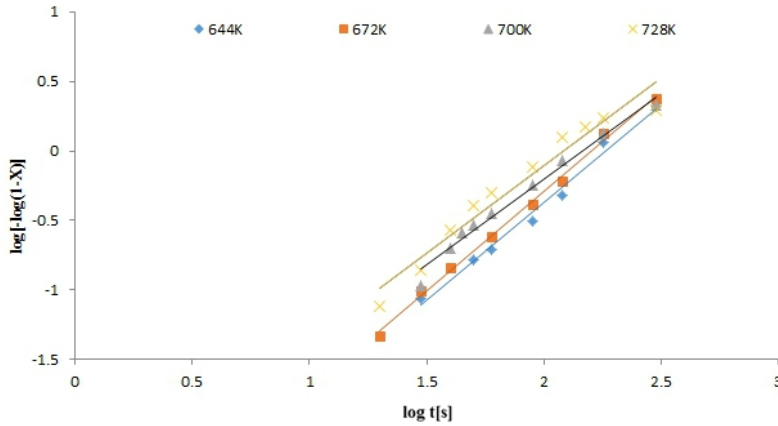
The values of k and n can be determined by the following rearrangement of the “Avrami” equation (Milosan, 2008, Ioan, 2014):

$$\log[-\log(1 - X)] = (n \log k + \log \log e) + n \log t \tag{3}$$

The $\log[-\log(1 - X)]$ versus $\log t$ at different temperatures are shown in Figure 7.



(a)



(b)

Fig.7 The plot of “log [−log(1 − X)] versus “log t(s)” for various austempering temperatures : a) 561K, 589K, and 617K, b) 644K, 672K, 700K, and 728K

The linear regression equations are shown as follows:

$$Y_{561} = -3.843 + 1.5629 * X, R^2 = 0.983$$

$$Y_{589} = -3.7384 + 1.5543 * X, R^2 = 0.998$$

$$Y_{617} = -3.9046 + 1.6386 * X, R^2 = 0.995$$

$$Y_{644} = -3.1943 + 1.4117 * X, R^2 = 0.988$$

$$Y_{672} = -3.1674 + 1.4372 * X, R^2 = 0.996$$

$$Y_{700} = -2.6859 + 1.2416 * X, R^2 = 0.983$$

$$Y_{728} = -2.6344 + 1.265 * X, R^2 = 0.951$$

The “k” and “n” values which are determined from the slopes and intercepts with the Y axis are listed in Table 2.

Table 2: The values of “n” and “k” for bainite formation

Temperature	n	k [1/s]
561K	1.5629	5.908×10^{-3}
589K	1.5543	6.705×10^{-3}
617K	1.6386	6.868×10^{-3}
644K	1.4117	9.824×10^{-3}
672K	1.4372	1.113×10^{-2}
700K	1.2416	1.339×10^{-2}
728K	1.265	1.592×10^{-2}

The minimum energy which allows the atoms to start the chemical reaction is the activation energy. According to the “Arrhenius” equation, the formula of activation energy and specific reaction rate is shown as follows (Milosan, 2008):

$$K = A * e^{-Q/RT} \tag{4}$$

Where: K – Rate constant which depends on temperature

A - Reaction frequency factor [1/s]

R- General gas constant 8.31 [J/mol * K]

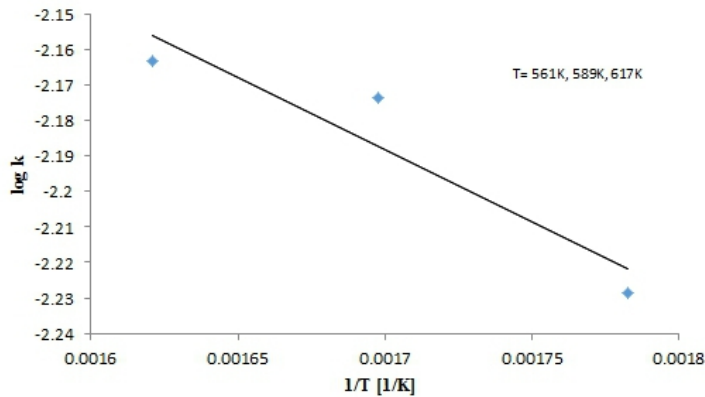
Q - Activation energy

T- Temperature [K]

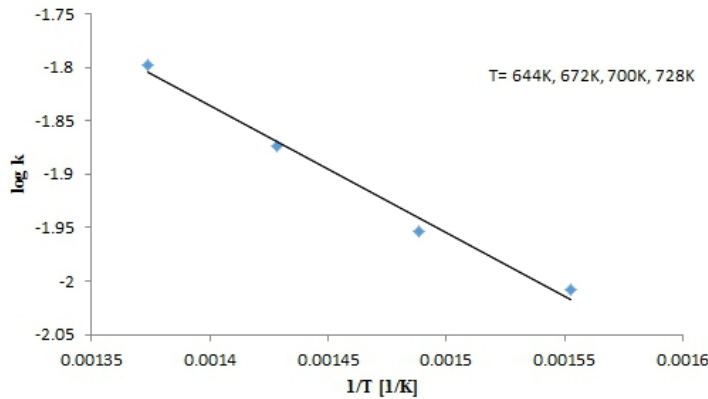
To determine the value of Q and A, the Arrhenius equation can be rewritten (Milosan, 2008):

$$\log k = -\log e \frac{Q}{RT} + \log A \tag{5}$$

The relationship between log k and 1/T is shown in Figure 8.



(a)



(b)

Fig. 8 The linear relationship between log k and 1/T: a) 561K, 589K, and 617K, b) 644K, 672K, 700K, and 728K

Based on equation 5, the values of Q (activation energy) and A (reaction frequency factor) can be determined by the slope of the regression line and intercept with the Y axis, see Table 3.

Table 3: The values of activation energy Q and reaction frequency factor A

Material	Q ($\frac{J}{mol}$)	A (1/s)
5160 (561K-617K)	7.81×10^3	3.2×10^{-2}
5160 (644K-728K)	2.26×10^4	6.62×10^{-1}

Conclusion

The bainite transformation kinetics in 5160 steel with various holding times at different austempering temperatures were studied, the results can be summarized as follows:

- Based on the microstructure observation, lower bainite was formed at 561K, 589K, and 617K, however, at 672K, 700K, and 728K, upper bainite was formed. Two types of bainite: upper bainite and lower bainite were observed at 644K.
- The transformation fraction results show that as the temperature increases, the bainite transformation occurs faster.
- The bainite transformation kinetics were determined by the “Avrami” equation and “Arrhenius” equation.
- For the range of 561K to 617K austempering temperatures, the frequency factor is 3.2×10^{-2} (1/s) and the 5160 steel requires an activation energy of $7.81 \times 10^3 \frac{J}{mol}$
- From 644K to 728K, the frequency factor is 6.62×10^{-1} (1/s) and the 5160 steel requires an activation energy of $2.26 \times 10^4 J/mol$

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