Modeling of the Bainite Transformation kinetics in C-Mn-Mo-Ni Steel weld CGHAZ

S. Uhm, C. Lee, J. Kim and J. Hong

Abstract

A metallurgical model for bainite transformation kinetics in the coarse-grained heat affected zone(CGHAZ) on the basis of an Avrami-type equation was studied. Isothermal transformation tests were carried out to obtain the empirical equations for incubation time and Avrami kinetic constants for C-Mn-Mo-Ni steel. The effect of prior austenite grain size(PAGS) on the reaction rate of bainite was also investigated.

Compared with experimental transformation behavior of bainite, the predicted behavior was in good agreement. It was also found that a smaller grain size retard the bainite reaction rate, contrary to the classical grain size effect and this is considered to be caused by constraint of grain size to bainite growth.

Key Words : Metallurgical modeling, Avrami equation, Bainite, Prior austenite grain size(PAGS), Heat affected zone(HAZ)

1. Introduction

Most materials for structural members have been fabricated by fusion welding. It has been reported that the HAZ (Heat affected zone), which has different microstructural and mechanical properties, is formed by a severe welding thermal cycle; CGHAZ (Coarse-grained HAZ) particularly has dominant effects on the safety of a welded structure[1-2].

Modeling for prediction of HAZ-properties has recently been studied, based on the concept that the changes of mechanical properties are caused by the effect of welding thermal cycle on the resulting microstructure. These microstructural changes are followed by phase transformation and then, there were several attempts at modeling the transformation kinetics of austenite theoretically and/or empirically[3-8].

This research has been mainly confined to isothermal transformation due to the ease of both the experimental and theoretical interpretation. The following Avrami-type equation has been used to describe the behavior of isothermal reaction[5-9], including the effect of prior austenite grain size (PAGS):

$$X = 1 - \exp[-\frac{k}{d_\gamma^m} \cdot (t-\tau)^n],$$

X : Fraction transformed t : Transformation time

τ : Incubation time d_γ : PAGS

n, m, k : Constants experimentally determined

In general, k is known as a rate constant which represents the nucleation and growth rate and n as a reaction constant, which is related to the morphology of transformed phase and the condition of nucleation. PAGS exponent, mindicates the effect of grain size on the reaction rate.

To apply this Avrami-type equation to the non-isothermal process, the additivity rule, which regards a non-isothermal cycle as be the summation of a series of short isothermal fractions[10], has generally been used[5-8].

Many studies for ferrite and pearlite transformation have been carried out with success[5-8]. However, there were few works for bainite which attention has been paid due to superior mechanical properties.

It is the intent of this study to evaluate the applicability of Avrami-type equations in predicting the volume fraction of bainite in the weld CGHAZ and to investigate the effect of PAGS on the reaction rate of bainite.

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2. Experiments

In order to examine the bainite transformation, C-Mn-Mo-Ni steel(SA508-cl.3) was selected due to its high hardenability and its compositions are shown in Table 1. The Ms (martensite-start) and Bs (bainite-start) temperatures, which are determined by preliminary continuous cooling transformation tests, are also indicated.

Table 1 Chemical compositions and start temperatures for martensite and bainite

Elements	C	Si	P	S	Mn	Cr	Ni	Mo	V	Cu	Al	Fe	Ms(°C)	Bs(°C)
Compositions	0.20	0.26	0.007	0.002	1.34	0.15	0.86	0.49	0.005	0.04	0.022	Bal.	400	580

Both the isothermal and continuous cooling transformation kinetics were measured by a dilatometer system. Cylinder type specimens, with dimensions of 3mm diameter by 10mm length, were employed to minimize the thermal gradient.

Isothermal transformation tests were conducted below Bs temperature to determine the kinetic constants and incubation time of Avrami-type equation as shown in Fig. 1. The peak temperature was selected to be 1350°C, a representative temperature of CGHAZ, and the holding times at the peak temperature were changed to study the effect of PAGS on bainite reaction rate. The measured grain sizes are 210, 370, 520 and 790㎛ for holding times 1, 5, 15 and 60 sec, respectively.

Continuous cooling transformation tests were carried out to assess the predicted behavior of bainite from isothermal kinetic data. Specimens transformed isothermally or continuously were etched by nital and picral solution. Then, microstructures were observed and the volume fractions of bainite were measured.

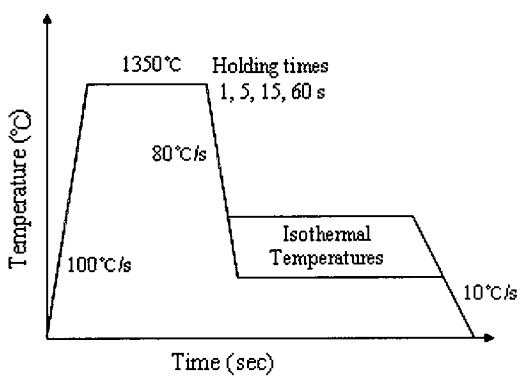


Fig. 1 Schematic thermal cycle for isothermal transformation tests

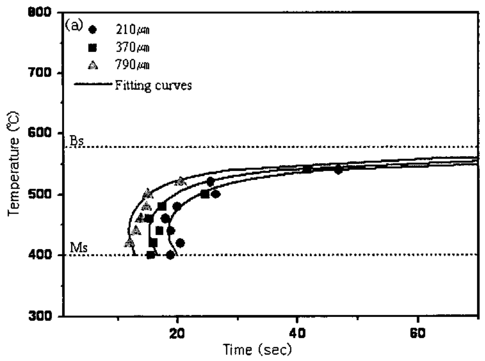
3. Results and discussion

After isothermal transformation tests, incubation time and kinetic constants such as n and k for each temperature were measured by analyzing the dilatometry. Fig. 2 shows these results. PAGS has an effect on the incubation times and rate constants, whereas reaction constant seems to be independent of grain sizes. This is natural because the incubation time and rate constant are related to the reaction rate while reaction constant is irrelevant to the rate.

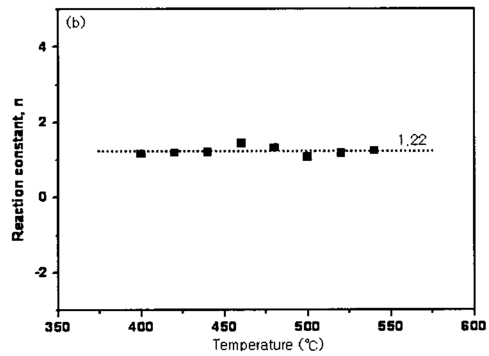
In Fig. 2(a) and (c), it is found that as PAGS increases, incubation time decreases and reaction constant increases, i.e., the increase of PAGS accelerates the reaction rate of bainite. This phenomenon is, however, in contrast of the classical PAGS effect on the reaction rate; reaction rate increases with decreasing PAGS due to the enhancement of the nucleation rate.

To confirm this effect, the time to approach 50% reaction is plotted against various PAGSs for representative temperatures in Fig. 2(d). The slope of this curve indicates the PAGS exponent and shows negative value around -0.38 as known in Fig. 2(c).

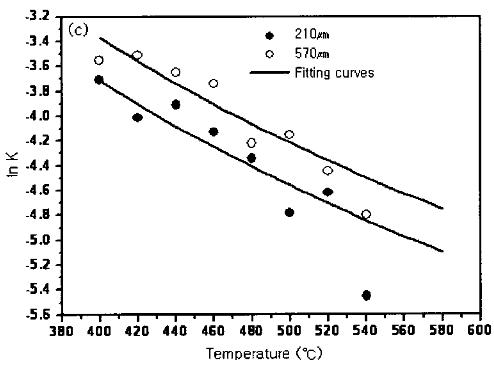
For the effect of grain size on bainite reaction, some[11-12] reported that bainite reaction was promoted by decreasing the grain size which causes the increase of the number density of grain boundary nucleation sites. Others[13,14] observed that a smaller austenite grain size retard the bainite reaction. In spite of these investigations, the effect of grain size has not clearly elucidated. However, it was demonstrated[14] recently that steels, which show opposite effects of grain size, have distinct differences in microstructures caused by the relationship between nucleation rate and growth rate; when the growth rate of bainite sheaves is relatively high compared with nucleation rate as schematically shown in Fig. 3(a), the bainite reaction was accelerated with increasing PAGS. On the other hand, when the growth rate is not so high as shown in Fig. 3(b), a smaller PAGS increases the reaction rate. It was proposed from these observations that PAGS has an effect not only on the number density of nucleation site but also on the maximum volume of a sheaf which forms from each grain boundary nucleus and the effect of PAGS rely on the dominant process of the two.



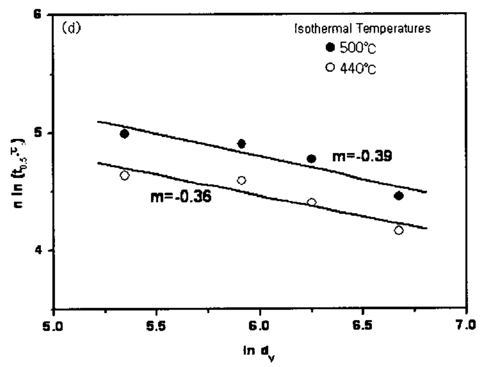
(a) Incubation times, τ



(b) Reaction constant, n



(c) Rate constant, k



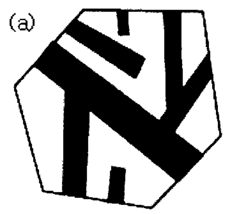
(d) Effect of PAGS on the time to 50% reaction

Fig. 2 Results of isothermal transformation tests

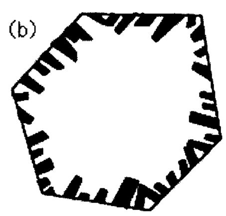
Although more investigations are required, the observed results in Fig. 2(c) and (d) seem to be rationalized as the dominant effect of PAGS on the maximum volume of a bainite sheaf.

From these analyses of isothermal transformation for bainite, empirical constants for SA508-cl.3 such as incubation time, reaction constant and rate constant are formulated as shown in Table 2.

A model for prediction the transformation behavior of bainite in the CGHAZ of SA508-cl.3 was established, based on the Avrami-type equation, additivity rule and empirical constants. The reliability of the model was evaluated by comparing with the behavior of continuous cooling transformation.



(a) When the growth rate is relatively high compared with nucleation rate



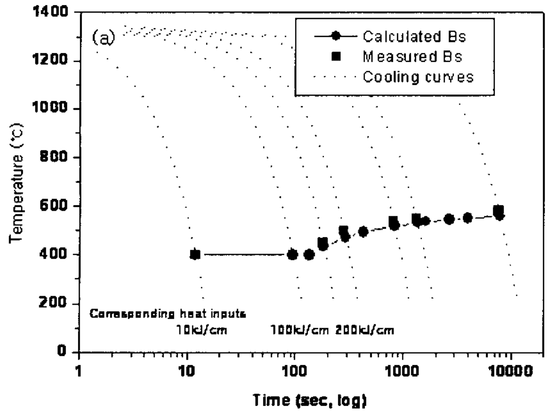
(b) When the growth rate is not so high compared with nucleation rate

Fig. 3 Schematic morphology of bainite sheaves at early stage of isothermal transformation [14].

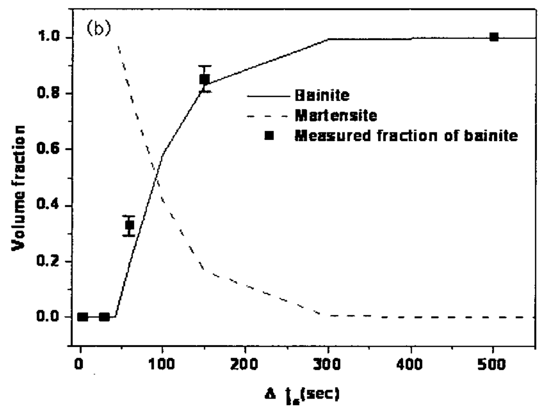
Table 2 Empirical equations determined by isothermal transformation tests for SA508-cl.3

Parameters	Empirical equations
Reaction constant, n	n=1.22
Rate constant, K	$K=[4.50\times10^{-6}\times\exp(8784/RT)]/d_\gamma^{-0.38}$
Incubation time, τ	$\ln\tau=7.03+1783.82/T-1.30\ln(\Delta T)-0.33\ln d_\gamma$

Fig. 4 shows the predicted start temperatures for bainite and volume fractions of bainite at various cooling times, which are indicative of welding heat input. Experimentally measured data are also indicated. It is found that the predicted results are consistent with measured values.



(a) Transformation start temperatures for bainite



(b) Volume fractions of bainite for 210μm PAGS

Fig. 4 Evaluation of the established model

4. Summary

The isothermal transformation kinetics of bainite could be characterized by Avrami-type equation, including the effect of PAGS on reaction rate; the empirical equations of kinetic constants for SA508-cl.3 could be obtained as shown in Table 2.

Bainite transformation behaviors in the CGHAZ which were predicted by Avrami-type equation with the additivity rule were in good agreement with experiments.

From analyzing the isothermal transformation kinetics, it was also found that the reaction rate of bainite decreased with decreasing PAGS, contrary to the classical effect of PAGS on reaction rate. Although more investigations are required, this phenomenon seems to occur because the effect of PAGS on the maximum volume of a bainite plate is more dominant than effect on the number density of nucleation site.

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