Microstructural Characteristics and Prediction of Austenite Grain Size in Heat Affected Zone of High Strength Low Alloy Steel

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High strength low alloy steel in direct quenched and tempered condition was welded using gas shielded arc welding process at different welding heat inputs. The austenite grain size adjacent to fusion line was measured in order to calculate the apparent activation energy Q_{app} for grain boundary movement, the time exponent n and the kinetic constant K . The austenite grain size in heat affected zone was evaluated using these calculated parameters, and was compared with the austenite grain size measured in real heat affected zone of joint. The microstructure changes in heat affected zone were studied. Results indicated that the calculated parameters can be used to the predication of austenite grain size in heat affected zone area heated to a temperature of above 1 100°C. The prediction results have a good agreement with measurement, while calculation at low temperatures was poor.

KEY WORDS: heat affected zone; austenite grain size; welding heat input; welding thermal cycle.

1. Introduction

Austenite grain in heat affected zone (HAZ) of base plate grows under the action of welding thermal cycle during welding, which is a significant factor to determine the microstructure and mechanical properties of the joints. Because the grain size in weld metal is controlled by that in HAZ, as well as the temperature and kinetics of phase transformation during cooling are influenced by the austenite grain size.^{1–3)} Various zones of the HAZ produce different microstructure and mechanical properties.

Isothermal austenite grain growth model has been investigated commonly by means of isothermal test. Also, thermo-mechanical processes such as reheating have been performed by previous researches to study the prediction model of austenite grain growth. While during welding processes the temperature will change continuously with time, which makes predictions of the HAZ austenite size growth behavior rather complicated. The prediction model of austenite grain size in the HAZ based on the Arrhenius type rate equation modulated for non-isothermal heating and cooling conditions is given as follow^{4–8)}:

$$D^{1/n} - D_0^{1/n} = K \int_{t_1}^{t_2} \exp\left(-\frac{Q_{\text{app}}}{RT(t)}\right) dt \quad \dots\dots\dots(1)$$

where D is the final mean austenite grain size, D_0 the initial austenite grain size, n the time exponent, K the kinetic constant, Q_{app} the apparent activation energy for grain boundary movement, $T(t)$ the local temperature cycle as a func-

tion of time t . The value t_1 and t_2 used in the integral refer to the time limits within which $T(t)$ resides in the austenite regime. The dwell time t_γ of the temperature cycle $T(t)$ in austenite can be obtained through $t_\gamma = t_1 - t_2$. The other symbols have their usual meaning. The time exponent n approached a constant value of 0.5 in ultrapure metals annealed at very high temperatures.^{9,10)}

Considering the complexity of temperature cycle in the HAZ, it is hard to obtain reliable experimental data of $T(t)$. Thus, as a simplification, the general Rosenthal equation of thick plate arc welding which provided a reasonable estimated of the temperature–time pattern within the HAZ of single pass steel welds was considered.^{9,11,12)} $T(t)$ corresponding to a given welding heat input and location can be calculated by utilizing the following equation:

$$T(t) - T_0 = \frac{Q}{2\pi\lambda vt} \exp\left(-\frac{r^2}{4at}\right) \quad \dots\dots\dots(2)$$

where T_0 is the ambient temperature, λ the thermal conductivity, a the thermal diffusivity, Q the net power received by the weldments, v the welding speed. So the predication of austenite size in HAZ can be done by connecting the two components, i.e. the heat flow model and the structural kinetic model.

In the current paper, high strength low alloy steel was welded using different welding heat input without pre-heating. The microstructure and austenite grain size in HAZ were investigated by optical microscope. The parameters Q_{app} , n and K were obtained by using measured austenite

Table 1. Chemical composition of steel and welding wire used in the test.

Material	Chemical composition (wt., %)									
	C	Mn	Si	Cr	Ni	Mo	Ti	P	S	Fe
Q690 steel	0.09	1.47	0.24	0.43	0.26	0.32	—	0.020	0.009	Balance
MK-G60-1	0.09	1.70	0.65	0.09	—	—	0.11	0.011	0.017	Balance

grain sizes next to the fusion line. And the austenite grain size in the HAZ was calculated. The calculated austenite grain size was compared with the measured grain size.

2. Experimental Materials and Procedure

The base metal used in the test was high strength low alloy steel Q690 with a thickness of 20 mm in direct quenched and tempered condition. MK-G60-1 welding wire with diameter of 1.2 mm was employed during gas shielded arc welding. The chemical composition of Q690 and welding wire is provided in **Table 1**. For simplified calculation, the base metal and weld metal are supposed to have the same physical properties: thermal conductivity $\lambda=0.025 \text{ W}/(\text{mm}\cdot^\circ\text{C})$, thermal diffusivity $\alpha=5 \text{ mm}^2\cdot\text{s}^{-1}$, volume heat capacity $\rho c=0.005 \text{ J}/(\text{mm}^3\cdot^\circ\text{C})$. The melting temperature (T_m) and the austenitising temperature (A_{c3}) of the base metal can be evaluated by the following equations¹³⁾:

$$T_m = 1573 - 90\%C \dots\dots\dots(3)$$

$$A_{c3} = 910 - 203\sqrt{\%C} - 15.2(\%Ni) + 44.7(\%Si) + 31.5(\%Mo) \dots\dots\dots(4)$$

where $\%X$ is the concentration of the element X in the base metal. We can obtain that $T_m=1530^\circ\text{C}$ and $A_{c3}=866^\circ\text{C}$ by the Eq. (3) and Eq. (4).

Plates were prepared into V type groove angle (30°) with 10 mm root face and 2 mm root distance for a total 60° included angle. The groove geometry of butt joint is illustrated in **Fig. 1**. The grooves were well prepared by machining and were brushed before welding using stainless steel wire wheel. The welding of plates was conducted using NBC-500 arc welding machine and the joints were formed by gas shielded arc welding process without pre-heating. The shielding gas was $80\%\text{Ar}+20\%\text{CO}_2$ with the flow of $18\text{--}20 \text{ L}\cdot\text{min}^{-1}$. The ambient temperature was 20°C . Three kinds of welding heat input were employed by adjusting welding speed. The welding parameters used in the test were listed in **Table 2**. The welding heat input was calculated as per equation¹⁴⁾:

$$E = \frac{\eta UI}{v \times 1000} \dots\dots\dots(5)$$

where E is the welding heat input ($\text{kJ}\cdot\text{cm}^{-1}$), η the arc efficiency factor, U the arc voltage (V), I the welding current (A), v the welding speed ($\text{cm}\cdot\text{s}^{-1}$). The net power received by the weldments $Q=\eta UI$. The parameter η takes 0.8 according to the used welding method.¹⁵⁾

The obtained weldments were cut into specimens *via* electro-discharge machining for subsequent handling. The specimens were ground and polished, mounted as metallographic samples using standard metallographic procedure,

Fig. 1. Groove geometry of butt joint (all dimensions are in mm).**Table 2.** Welding parameters used in the test.

No.	Welding current	Arc voltage	Welding speed	Heat input
	I/A	U/V	$v/\text{cm}\cdot\text{s}^{-1}$	$E/\text{kJ}\cdot\text{cm}^{-1}$
S	290	30	0.59	11.8
M	290	30	0.53	13.1
L	290	30	0.44	15.8

Fig. 2. Microstructure of the base metal showing bainite, polygonal ferrite and high carbon constituents.

and then etched with 5% Nital solution. Microstructure in the HAZ was analyzed by means of Nikon AFX-IIA metalloscope. Austenite grain sizes were measured by quantitative image analyzer (Image-Pro Plus).

3. Results and Discussion

3.1. Microstructure of the Base Metal

The initial microstructure by optical microscopy of the steel used in the test is exhibited in **Fig. 2**. The microstructure seems to consist of bainite with polygonal ferrite (PF) and colonies of high-carbon constituents. The austenite grains were elongated apparently due to manufacturing processes of the base plates. As the direction of welding perpendicular to that of elongated grain, the mean austenite grain size D_0 was measured to be $15 \mu\text{m}$.

3.2. Austenite Grain Size in HAZ Next to the Fusion Line

Microstructure of the HAZ adjacent to the fusion line is shown in **Fig. 3**. The microstructure of coarse grained HAZ seems to be aligned structure consisting of parallel bainitic

ferrite laths separated by elongated and massive second phase particles. The sheaves of bainitic ferrite lath in different directions divided the austenite grain into different areas, which could be seen in Fig. 3. The air cooling of the HAZ from high austenitising temperature and the high cooling rate was expected to produce coarse bainite structure. The bainitic ferrite became coarse with the increase of heat input. The coarse transformation structures within austenite grain could be attributed to the combination of large prior austenite grain size and a limited number of nuclei sites. The austenite grain size in the HAZ next to the fusion line was measured *via* Image-Pro Plus software. When the welding heat input was respective $11.8 \text{ kJ} \cdot \text{cm}^{-1}$, $13.1 \text{ kJ} \cdot \text{cm}^{-1}$ and $15.8 \text{ kJ} \cdot \text{cm}^{-1}$, the corresponding measured mean austenite grain size in HAZ next to fusion line

Fig. 3. Microstructure of the HAZ adjacent to the fusion line at different net heat input (a) $E=11.8 \text{ kJ} \cdot \text{cm}^{-1}$, (b) $E=13.1 \text{ kJ} \cdot \text{cm}^{-1}$ and (c) $E=15.8 \text{ kJ} \cdot \text{cm}^{-1}$.

was $82 \mu\text{m}$, $88 \mu\text{m}$ and $95 \mu\text{m}$.

3.3. Calculation of Parameters for Grain Growth Model

When considering $\partial T(t)/\partial t=0$ for Eq. (2), the temperature reaches the peak value T_p . Thus the following equation can be obtained from Eq. (2):

$$r_p^2 = \frac{2Q}{\epsilon \pi \nu \rho c (T_p - T_0)} \dots\dots\dots (6)$$

where r_p is the distance from the weld center where the peak temperature is T_p . Taking the peak temperature as the melting temperature of the base metal, *i.e.* $T_p=T_m$, the weld half width at different heat inputs can be obtained according to Eq. (6) as listed in **Table 3**. Also the parameters t_1 and t_2 for the three heat inputs can also be calculated *via* MATLAB software by taking $T(t)=A_{c3}$. The temperature cycle curves for different heat inputs at the HAZ next to fusion line can be seen in **Fig. 4**, which are obtained from Eq. (2) by utilizing ORIGIN software.

Combining Eq. (1), Eq. (2), Table 1 and Table 3, three equations as functions of Q_{app} , n and K can be got. We solved the set of equations by means of MATLAB software, and the results are: $Q_{app}=249 \text{ kJ} \cdot \text{mol}^{-1}$, $n=0.35$, $K=9.12 \times 10^{13}$.

It is clear that the calculated time exponent is lower than the theoretical value (0.5). Other researchers have stated that the lower value of time exponent was attributed to several factors such as specimen thickness effect, pinning force by second phase precipitates, solute drag effect and so on.^{16–18} It is well known that alloying and impurity elements in the dissolved state and in the form of inclusions or second phase particles will hinder grain growth.^{19–21} Uhm *et al.* reported that the low time exponent is thought to be

Fig. 4. Temperature cycle curves for different heat inputs at the HAZ next to fusion line.

Table 3. Calculated parameters and measured austenite grain size in the HAZ next to the fusion line.

Heat input $E/\text{kJ} \cdot \text{cm}^{-1}$	Calculated weld half width r_{cm}/mm	t_1/s	t_2/s	t_f/s	Austenite grain size adjacent to fusion line $D/\mu\text{m}$
11.8	6.05	0.73	6.78	6.05	82
13.1	6.38	0.82	7.55	6.73	88
15.8	7.00	0.98	9.10	8.12	95

Table 4. Predication results of austenite grain size in HAZ at heat input of 13.1 kJ cm^{-1} .

Distance from fusion line /mm	Distance from weld center line /mm	t_1 /s	t_2 /s	t_p /s	t_r /s	T_p /°C	Calculated austenite grain size D / μm
0.1	6.48	0.86	7.46	2.10	6.60	1485	71.2
0.2	6.58	0.91	7.37	2.16	6.46	1441	57.8
0.3	6.68	0.95	7.27	2.23	6.32	1399	46.9
0.4	6.78	1.01	7.17	2.30	6.16	1358	38.2
0.5	6.88	1.06	7.07	2.37	6.01	1320	31.3
0.6	6.98	1.12	6.97	2.44	5.85	1283	25.9
0.7	7.08	1.18	6.86	2.51	5.68	1247	22.0
0.8	7.18	1.24	6.74	2.58	5.50	1213	19.2
0.9	7.28	1.31	6.62	2.65	5.31	1181	17.4
1.0	7.38	1.39	6.50	2.72	5.11	1149	16.3
1.1	7.48	1.47	6.37	2.80	4.90	1119	15.7
1.2	7.58	1.55	6.23	2.87	4.68	1091	15.3
1.3	7.68	1.64	6.09	2.95	4.45	1063	15.2
1.4	7.78	1.75	5.93	3.03	4.18	1036	15.1
1.5	7.88	1.86	5.77	3.10	3.91	1011	15

Fig. 5. Calculated and measured austenite grain size as a function of distance from fusion line ($E=13.1 \text{ kJ/cm}$).

caused by a solute drag effect by analyzing the equilibrium dissolution temperatures of carbides as well as impurity-drag theories.²⁾

3.4. Predication of Grain Size in the HAZ

The three parameters *i.e.* Q_{app} , n and K are supposed to be constants over the entire high temperature austenite grain phase. Therefore, the austenite grain size can be evaluated according to Eqs. (1) and (2). The calculated values including start time (t_1) and end time (t_2) of temperature in austenite regime, peak temperature (T_p) and austenite grain size (D) at different location in the HAZ at heat input of 13.1 kJ cm^{-1} were calculated and listed in **Table 4**. The calculated grain size as a function of distance from the fusion line is shown in **Fig. 5**.

The microstructure and prior austenite grains corresponding to different locations of the HAZ are exhibited in **Figs. 6a–6(f)**. For given steels, the type of microstructure within the HAZ area of a welded joint depends on the peak temperature of the thermal cycle and the cooling rate after welding. The HAZ area adjacent to the fusion line was heated to very high temperature. As a result, the cooling

Fig. 6. Microstructure and austenite grain size of various HAZ sections at about (a) 0.15 mm (b) 0.25 mm (c) 0.45 mm (d) 0.70 mm (e) 1.40 mm (f) 2.1 mm from the fusion line ($E=13.1 \text{ kJ/cm}$).

rate was small which gave rise to the formation of different kinds of bainite structure including lath bainite and granular bainite with a small amount of low carbon martensite. The bainite sheaves were coarse due to the large austenite grain. It could be seen that the bainite within austenite grain grown almost in the same direction perpendicular to fusion line because this is the direction of the maximum temperature gradient and hence maximum heat extraction. Bainitic ferrite with body centered cubic (bcc) crystal structure tended to grow in the easy-growth direction of $\langle 100 \rangle$.^{22,23)} Therefore, during solidification grains with their easy-growth direction essentially perpendicular to the fusion line will grow more easily and crowd out those less fa-

vorably oriented grains.

Other zone heated to a temperature of higher than A_{c3} consists of predominant lath martensite (LM) due to relatively larger cooling rate. The width of martensite laths became finer with the increase of distance from the fusion line because of different peak temperature and cooling rate. In the area subjected to a temperature in excess of A_{c1} and A_{c3} , partial phases in base metal transformed to austenite during heating stage. During the cooling phase of thermal cycle, fine lath martensite was formed within the austenite grain. Thus, the microstructure of this zone included lath martensite as well as preserved microstructure of base metal (*i.e.* bainite, polygonal ferrite and high carbon constituents). The subcritical HAZ was heated to a subcritical temperature below A_{c1} . As a result, no austenization phenomenon happened in this area where the main changes were precipitation and aggregation of carbides which induced the transformation of polygonal ferrite from bainitic ferrite.

It can be seen from Fig. 6 that austenite grains are characterized by distinct grain boundaries. Austenite grain size was measured at different locations in real HAZ and was marked in Fig. 5. Results shown predication of grain sizes at the locations where the peak temperature (T_p) was greater than 1100°C had a good correspondence with measured grain sizes. But for the regions where T_p was lower than 1100°C in HAZ, the agreement was poor. It was found that the measured grain size was smaller than predicted grain size at low temperature. This seems to be attributed to the fixed initial austenite grain size (15 μm), as mentioned in previous text. So in order to predict the grain size at lower temperatures precisely, the austenite grain size after austenite transformation should be predicted firstly. As stated by Uhm *et al.*,²⁾ this requires the information about the theories of nucleation and growth for phase transformation.

4. Conclusions

(1) Microstructure changes in HAZ from the fusion line to base metal were proved to be: lath bainite+granular bainite→lath martensite→lath martensite+bainite+polygonal ferrite+high carbon constituents→bainite+polygonal ferrite+high carbon constituents.

(2) The apparent activation energy Q_{app} for grain

boundary movement, the time exponent n and the kinetic constant K were calculated to be 249 kJ·mol⁻¹, 0.35 and 9.12×10^{13} respectively, by measuring prior austenite grain size in coarse grained heat affected zone next to the fusion line in the joints produced using different heat inputs.

(3) The calculated grain growth parameters can be used to the predication of austenite grain size in HAZ zones heated to peak temperatures of higher than 1100°C. The prediction results have a good agreement with measurement, while calculation at low temperatures was poor.

REFERENCES

- 1) G. Spanos, R. W. Fonda, R. A. Vandermeer and A. Matuszeski: *Metall. Mater. Trans. A*, **26A** (1995), 3277.
- 2) S. Uhm, J. Moon, C. Lee, J. Yoon and B. Lee: *ISIJ Int.*, **44** (2004), 1230.
- 3) M. Shome, O. P. Gupta and O. N. Mohanty: *Metall. Mater. Trans. A*, **35A** (2004), 985.
- 4) M. F. Ashby and K. E. Easterling: *Acta Metall.*, **30** (1982), 1969.
- 5) J. C. Ion, K. E. Easterling and M. F. Ashby: *Acta Metall.*, **32** (1984), 1949.
- 6) O. M. Akselsen, Ø. Grong, N. Ryum and N. Christensen: *Acta Metall.*, **34** (1986), 1807.
- 7) I. Adnerson and Ø. Grong: *Acta Metall.*, **43** (1995), 2673.
- 8) M. Shome, O. P. Gupta and O. N. Mohanty: *Scr. Mater.*, **50** (2004), 1007.
- 9) Ø. Grong: *Metallurgical Modeling of Welding*, 2nd Edition, The institute of Materials, London, (1997), 337.
- 10) D. A. Porter and K. E. Easterling: *Phase Transformations in Metals and Alloys*, 2nd Edition, Chapman & Hall, London, (1992), 140.
- 11) D. Rosenthal: *Weld. J.*, **20** (1941), 220s.
- 12) D. Rosenthal: *Weld. J.*, **68** (1946), 849.
- 13) W. C. Leslie: *The Physical Metallurgy of Steels*, McGraw-Hill Publication, New York, (1982), 273.
- 14) E. F. Nippes: *Metals Handbook, Welding, Brazing and Soldering*, Vol. 6, ASM International, Metal Park, OH, (1983), 31.
- 15) N. Christensen, V. de L. Davies and K. Gjermundsen: *Br. Weld. J.*, **12** (1965), 54.
- 16) J. E. Burke: *Trans. Met. Soc. AIME*, **180** (1949), 73.
- 17) C. S. Smith: *Trans. Met. Soc. AIME*, **175** (1948), 15.
- 18) H. Hu and B. B. Rath: *Metall. Trans.*, **1** (1970), 3181.
- 19) J. W. Cahn: *Acta Metall.*, **10** (1962), 789.
- 20) K. Lücke and H. Stüwe: *Recovery and Recrystallization in Metals*, Interscience, New York, (1963), 131.
- 21) E. Nes, N. Ryum and O. Hunderi: *Acta Metall.*, **33** (1985), 11.
- 22) A. L. Schaeffler: *Metal Prog.*, **56** (1949), 680.
- 23) S. Kou: *Welding Metallurgy*, 2nd edition, John Wiley and Sons, New York, (2003), 171.