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Research Article

Variable Analysis for Grain Size Prediction of Austenitic Stainless Steel SS316l Using Heat Treatment

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Abstract

Background and Objective: The properties of SS316L stainless steel plate are significant due the wide range of usage of the stated material. It can be governed by the chemical composition and microstructure. This study deals with the investigation of major parameters used for predicting the grain size of austenitic stainless steel SS316L at different temperature range. The major grain growth variables such as; kinetic exponent and grain growth rate constant had been studied to interpret the mechanism in the samples with different heat treatment settings. **Materials and Methods:** The material investigated was austenitic stainless steel SS316 L. Samples were isothermally held at various temperatures and holding time. **Results:** Based on the results, the kinetic rates were plotted by using the Arrhenius equation to predict the grain size. Using this method the estimated grain size shows an acceptable error percentage up to 12.5% for temperature at 1100°C and for the temperature of 1200°C or above. **Conclusion:** it is concluded the grain growth will be abnormal at higher temperature range, the precipitate that occurs at the grain boundary layer can be implemented for a modified Arrhenius equation.

Key words: Grain size, grain growth exponent, austenitic stainless steel, kinetic exponent, activation energy

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

The properties of SS316L stainless steel plate are important due the wide range of usage of the stated material. The presence of precipitation such as; carbides and nitrides at grain boundaries is considered for commercial importance[1,2]. As such, the importance of microstructure has a large effect towards the mechanical properties and for this reason, it is important to control the grain size. For instance, the yield strength, hardness, fatigue strength, tensile strength and impact strength are increased with decreasing of grain size[3]. On the other hand, one of the most important factors controlling austenite grain structure at the end of cold-working and annealing operations is the austenite stability with respect to strain induced transformation[4]. Consequently, to improve the strength of a material is to make the grains as small as possible by increasing the amount of grain boundary. Small grain sizes are accompanied by high volume of grain boundaries and as a result, the more grain boundaries that be present, the higher the strength becomes. Previous research has indicated the grain growth behavior at elevated temperature has been investigated and an attempt to model the recrystallization and grain growth of steels by using various models such as; the Potts (Monte Carlo) model and Arrhenius model[5,6]. As to austenitic stainless steels, several studies have been reported on the mechanical properties and grain growth behaviour[7,8]. However, less information can be gathered about the grain size before and after the heat treatment process that includes transformation process, especially at the range of in between 1173 K and 1273 K (900 and 1000 °C) when the recrystallization process and long-term temperature exposures happens. As one of the important parameters to be controlled when specific mechanical properties is required for steel is the austenitic mean grain size.

The objective of this research was to predict the austenitic mean grain size by using the grain growth formula based on locally sourced material and verify its variable value for future use. Furthermore, the variable concluded from this research will be used for numerical computation algorithm of grain growth formula.

MATERIALS AND METHODS

Experimental site: The research was carried out at Chair of Welding Department of Engineering, Technische Universitat Chemnitz from June-July, 2019.

Materials and research tools: The material used for this experimental work was a SS316L stainless steel plate supplied by Irfan Bina Enterprise. The steel was supplied as hot-rolled plate with a thickness of 4 mm. The chemical composition of the plate was analyzed by Arc Spectrometer (Q4 Qantas). Sample were heat treated by using a DIL 805A/D quenching and deformations dilatometers. Microstructural observation was conducted with Leica optical microscope integrated with Leica Material Workstation software. Microstructural images were captured by an optical microscope Olympus BX60.

Research procedure: All research procedure was following the guidelines provided by American Society for Testing and Materials (ASTM) related to grain size standards.

Data collection: The actual austenite grain sizes were determined according to ASTM E112 by Leica Material Workstation by using the single circle method while the estimated austenite grain size was obtained from statistical analysis of Arrhenius equation[5,6].

Experimental design: In order to predict the grain size of the tested austenite stainless steel at elevated temperature, SS316L stainless steel plate with a thickness of 4 mm were isothermally held at temperature of 1173 and 1273 K (900 and 1000 °C) for various time (30, 60, 120 and 240 sec). The data obtained from the experiment can be used to predict the mean grain size at different temperature.

Parameters measured: From the classical theory of normal grain growth, the grain growth kinetics after primary recrystallization can be described in the following form[9]:

$$D = (Kt)^n \quad (1)$$

where, D is the mean grain size obtained by holding time t, is a grain growth rate constant and n is the grain growth kinetic exponent. The apparent activation energy Q for grain growth can be described by an Arrhenius equation:

$$K = k_0 \exp\left(-\frac{Q}{RT}\right) \quad (2)$$

where, k_0 is a constant, T is the temperature and R is the universal gas constant.

RESULTS

Material verification: The chemical composition result obtained from the QMatrix Analysis Machine in weight

Table 1: QMatrix analysis results for SS316L stainless steel plate (weight percent)

C	Si	Mn	P	S	Ni	Cr	Mo	Fe
0.017	0.340	1.475	0.026	0.069	10.19	16.76	2.148	68.44

Table 2: Average grain size

		Holding time (sec)			
Temperature (°C)		30	60	120	240
K	1173 (900)	20	25	27	30
	1273 (1000)	28	33	35	37

Table 3: Values of K, n and fitted K* and n* for the tested SS316L stainless steel plate

Temperature (°C)	K	n
1173 K (900)	1.23857	1.46131
1273 K (1000)	1.63392	1.10587
1373 K (1100)	1.86018*	1.09703*
1473 K (1200)	2.11618*	1.04577*

*K: Estimated grain growth rate constant value, *n: Estimated kinetic exponent value

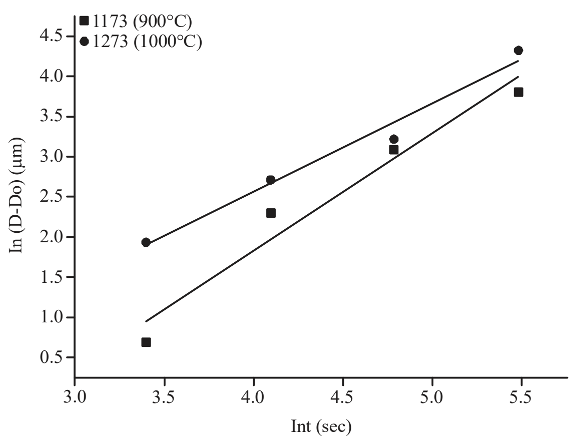

Fig. 1: Logarithmic plots of the grain size vs. the holding time after annealing at the annealing temperatures of 1173 K and 1273 K

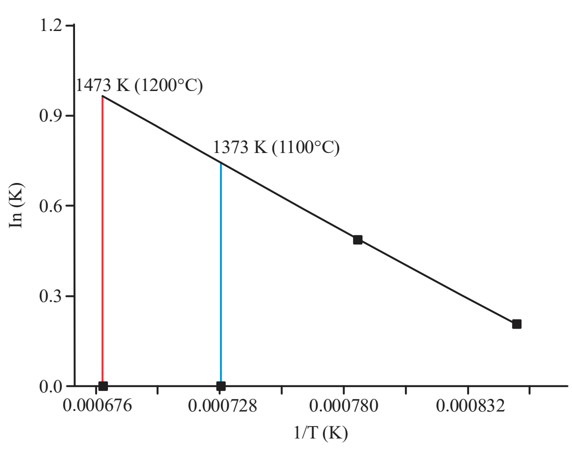

Fig. 2: Growth rate constant as a function of the reciprocal of the process temperature

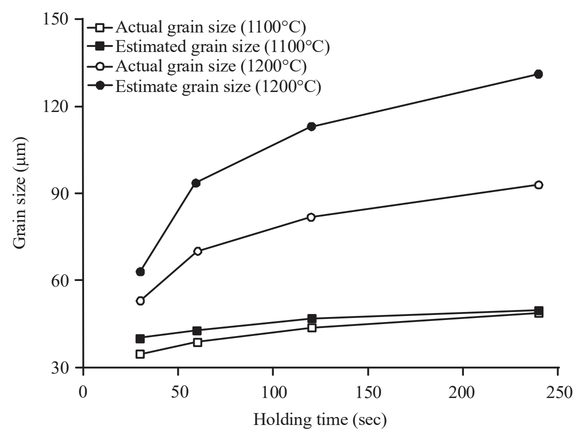

Fig. 3: Actual grain size vs. estimated grain size for different holding time

percent are according to the ASTM standard A240 for 316L stainless steel as shown in Table 1.

Austenitic stainless steel grain size: The austenite grain size after experiment for each sample was collected and shown in Table 2. An estimated value of K and n represented in Table 3 was obtained by using the Arrhenius equation to estimate the austenite grain size at temperature of 1100 and 1200°C.

The grain growth kinetic exponent was obtained from the slope of the straight line in log-log plots of the grain size vs time by using linear regression fit as shown in Fig. 1 as the graph plotted can be used to predict both of the values for other temperature range. The plot of the grain growth rate constant vs. the reciprocal of the temperature shows a linear relationship, as shown in Fig. 2 as higher the temperature the higher the grain growth constant value will be. Figure 3 presents the actual grain size vs. the estimated grain size value calculated by using the Arrhenius equation.

Figure 4 and 5 present the typical micrographs of austenite grain boundaries under different heating temperatures and holding times. It was observed austenite grain size can be calculated and grow gradually when annealing time increases from 30-240 sec. The result shows that austenitic stainless steel SS316L at the temperature of 1200°C or above will indicate an abnormal grain growth.

Grain size prediction: An estimated grain growth rate constant value of K* and estimated kinetic exponent value of n* have been obtained from the statistical analysis. An

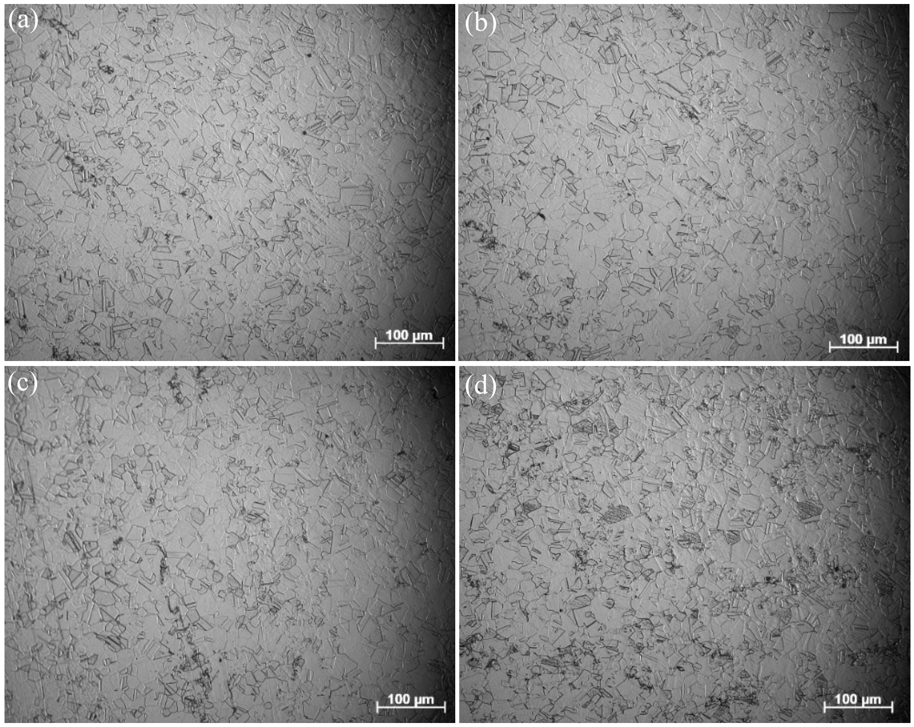

Fig. 4(a-d): Micrograph of austenite grain boundaries under different heat treatment conditions (a) 1173 K, 30 sec, (b) 1173 K, 60 sec, (c) 1173 K, 120 sec and (d) 1173 K, 240 sec

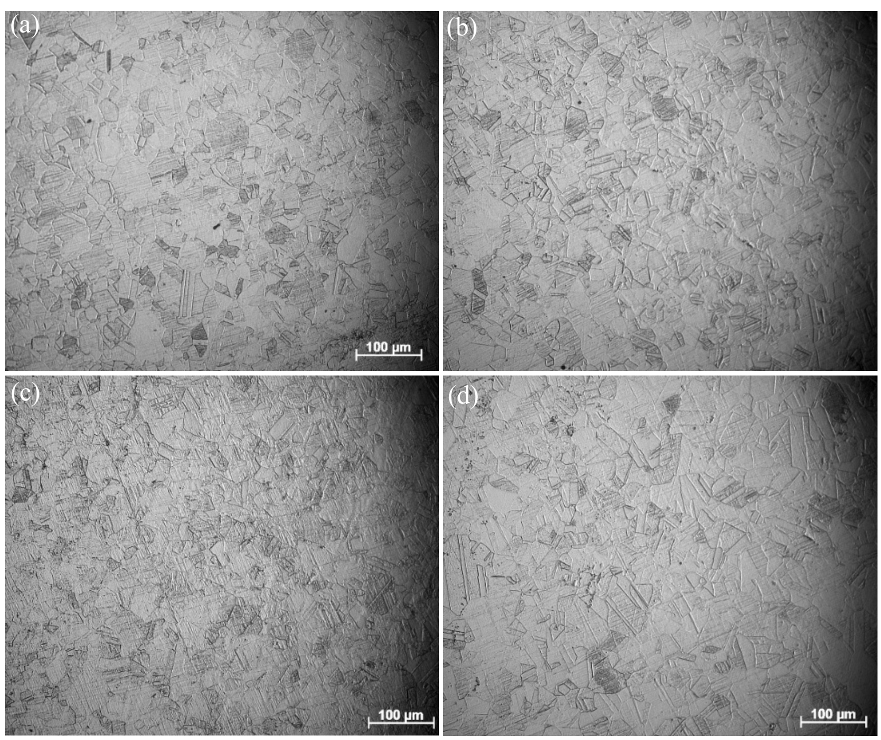

Fig. 5(a-d): Micrograph of austenite grain boundaries under different heat treatment conditions (a) 1273 K, 30 sec, (b) 1273 K, 60 sec, (c) 1273 K, 120 sec and (d) 1273 K, 240 sec estimated grain size at different temperature range can be calculated by using the Arrhenius equation. The percentage of error between actual and estimated grain size is shown in Fig. 3. It shows that the error percentage is increasing for each holding time above the temperatures of 1473 K (1200°C). It shows the grain growth of austenitic stainless steel SS316L was growing abnormally and can't be predicted by using the Arrhenius equation. This clearly indicates the presence of other particles at the grain boundary layer that slows down the grain growth kinetics.

DISCUSSION

The value of the predicted grain size at the temperature range of 900-1100°C was proven that it can be approximately calculated by using the Arrhenius equation[10-12]. At temperature above 1200°C the predicted grain size error percentage were higher and considered at an unacceptable range. This unique condition for austenitic stainless steel has been reported in previous studies and has been proven again to be the same condition for SS316L grade stainless steel[13-15]. Thus, a modification should be made to consider the existence of material precipitation in austenitic stainless steel SS316L at higher temperature range.

Previous studies on the grain size of bulk 316L stainless steel related to temperature evolution at high temperature range are mostly related to welding process[16]. As temperature rises, the grain growth rate increases, but at a certain temperature the grain growth behave abnormally considering the presence of other particles that respond only at higher temperature range[17,18]. The presence of other particles that prevent the grain boundaries from moving are the most common factors, thus the Arrhenius equation should be modified for austenitic stainless steel material category. According to previous studies, these main particles can mainly be very small sulfides, nitrides, carbides or silicate particles exist in the grain boundary of stainless steel material[4,17-19]. Future experiment will be planned at different temperature range to carry out the verification of the grain size of austenitic stainless steel SS316L at higher temperature while considering precipitation investigation at microstructural level. Thus, the grain size prediction can be expanded to higher temperature range to understand its grain growth behavior during high temperature evolution.

CONCLUSION

This study advances the idea that grain size can be predicted by using Arrhenius equation for austenitic stainless steel by investigating the material behavior at elevated temperature. Although, the grain growth will be abnormal at higher temperature range, the precipitate that occurs at the grain boundary layer can be implemented for a modified Arrhenius equation.

SIGNIFICANCE STATEMENT

This study discover the grain growth mechanism of SS316L is grain boundary migration as grain boundary can be completely consumed by surrounding grains while having irregular shape that can be beneficial for grain growth behaviour of austenitic stainless steel. This study will help the researcher to uncover the critical areas of austenitic stainless steel grain growth behaviour at elevated temperature that many researchers were not able to explore. Thus, a new theory on grain growth behaviour at elevated temperature for austenitic stainless steel may be arrived at.

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