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Thermal Cycle Simulation of Welded Products with Heat Treatment Process on AISI 1015 Low Carbon Steel

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ABSTRACT

In the welding of carbon steel, the cooling time from the highest temperature or peak temperature can be identified, where the cooling rate is generally represented in a welding thermal cycle. Knowledge of the welding thermal cycle greatly facilitates the understanding of the extent of differences in cooling rates at various applied peak temperatures.

The thermal cycle curve can be obtained through direct testing methods, namely by measuring the temperature on the welded plate. However, this method requires extensive equipment and a high level of precision. Therefore, the author conducted an experiment to obtain the thermal cycle curve using an alternative method. This method involves heat treatment, in which the cooling process is carried out in free air (*normalizing*) while varying the peak temperature for each specimen.

The specimens used in this study were AISI 1015 low-carbon steel, with dimensions of 100 × 20 × 20 mm for the larger specimens and 50 × 20 × 20 mm for the smaller specimens. The applied peak temperatures were 750°C, 800°C, 900°C, and 1000°C.

The experimental results showed that the cooling rate obtained through the heat treatment process was inversely proportional to that of the welding process. Therefore, determining the thermal cycle using the heat treatment process is not recommended.

Keywords: Welding Thermal Cycle , Heat Treatment , AISI 1015 Low Carbon Steel , Cooling Rate, Normalizing Process

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Introduction

Welding of low-carbon steel is widely used in engineering applications due to its good mechanical properties, weldability, and cost-effectiveness. During the welding process, the material experiences rapid heating and cooling, resulting in a thermal cycle that significantly influences the microstructure and mechanical properties of the welded joint. Understanding the welding thermal cycle is essential for analyzing cooling behavior and predicting material performance after welding. Conventionally, thermal cycle determination is conducted through direct temperature measurement on welded specimens, which requires sophisticated instrumentation, extensive experimental setup, and high measurement accuracy. To overcome these limitations, alternative methods are needed to simulate welding thermal behavior more efficiently. This study investigates the possibility of using heat treatment, specifically the normalizing process, as an alternative approach to simulate the thermal cycle of welding in AISI 1015 low-carbon steel. By varying the peak temperatures from 750°C to 1000°C and observing the cooling characteristics under free-air cooling conditions, the study aims to compare the thermal responses between the heat treatment simulation and actual welding conditions. The findings are expected to evaluate the feasibility of this method as a simplified thermal cycle simulation approach for welding studies

Literature Review

Welding is a process of joining two or more materials, particularly metals, through the application of heat, pressure, or a combination of both, resulting in the formation of a permanent metallurgical bond between the joined materials (1). During the welding process, the material undergoes a thermal cycle consisting of heating to high temperatures followed by cooling at a certain rate, which may cause changes in microstructure, residual stress, distortion, and mechanical properties in the weld zone and the *heat affected zone* (HAZ) (2). Therefore, understanding the welding thermal cycle is essential for analyzing weld quality and the behavior of welded materials (Lancaster, 1999).

In general, welding processes can be classified into several major categories, namely fusion welding, solid-state welding, resistance welding, and high-energy beam welding (3). Fusion welding is the most commonly used method, in which the base metal is melted with or without the addition of filler metal, such as in Shielded Metal Arc Welding (SMAW), Gas Metal Arc Welding (GMAW/MIG), Gas Tungsten Arc Welding (GTAW/TIG), and Submerged Arc Welding (SAW) (4). Solid-state welding refers to joining processes performed without melting the base material, such as friction welding and diffusion welding, which rely on pressure and heat generated by friction or atomic diffusion (Cary & Helzer, 2005). Meanwhile, resistance welding utilizes heat generated by electrical resistance at the joint area, such as in spot welding and seam welding (5). Each welding method produces different heat distributions and cooling rates, thereby affecting the resulting microstructure of the welded joint (6).

The material used in this study is AISI 1015 low-carbon steel. AISI 1015 belongs to the low-carbon steel group, containing approximately 0.15% carbon, which provides high ductility, good formability, and excellent weldability (5). Its low carbon content reduces the tendency for martensite formation during rapid cooling compared to medium- or high-carbon steels (Callister, 2007). This steel is widely used in structural components, shafts, automotive parts, and general fabrication applications due to its balanced combination of strength, ease of processing, and relatively low production cost (7). These characteristics make AISI 1015 suitable for studies related to thermal cycle simulation and welding processes.

Heat treatment is a process involving heating a material to a specific temperature, holding it for a certain duration, and then cooling it using a selected medium to achieve desired changes in mechanical properties and microstructure (8). One commonly used heat treatment method is normalizing, which involves heating steel above its critical temperature followed by cooling in still air (9). The normalizing process aims to refine grain size, improve microstructural homogeneity, relieve residual stresses, and enhance the mechanical properties of the material (10). In this study, the normalizing method is used as an alternative simulation approach to represent the welding thermal cycle through variations in peak temperature. However, the heat distribution in actual welding differs significantly from conventional heat treatment because welding involves a moving heat source that creates more complex localized thermal gradients (3).

The measuring instruments used in thermal cycle simulation studies greatly influence the quality of the obtained data. Thermocouples are commonly used temperature sensors for measuring temperature changes over time during heating and cooling processes (5). The recorded temperature data are typically collected using a data acquisition system to generate accurate thermal cycle curves (7). An electric furnace is used as a controlled heat source to achieve the required peak temperatures for the experiment (7). A stopwatch may be used to record cooling times over specific temperature intervals, particularly in manually monitored experiments (6). In addition, dimensional measuring tools such as vernier calipers are used to ensure that specimen dimensions conform to the experimental design, since specimen size affects heat transfer and cooling behavior 7).

Based on the literature review, thermal cycle simulation using heat treatment may serve as a simpler alternative to direct measurement during welding processes. However, because the heat transfer mechanisms between actual welding and conventional heat treatment differ fundamentally, the validity of this simulation method must be experimentally evaluated to determine its suitability in representing real welding conditions.

Research Method

This study employed an experimental method to simulate the thermal cycle of welding products using a heat treatment process on AISI 1015 low-carbon steel. The objective was to evaluate the feasibility of using heat treatment as an alternative method for representing the thermal cycle experienced during welding by comparing cooling characteristics at different peak temperatures.

1. Research Materials

The material used in this study was AISI 1015 low-carbon steel, selected due to its excellent weldability, good ductility, and common application in engineering structures. The chemical composition and thermal response of this material make it suitable for thermal cycle simulation studies.

The specimens were prepared in two different dimensions:

- Large specimen**:** 100 mm × 20 mm × 20 mm
- Small specimen**:** 50 mm × 20 mm × 20 mm

The variation in specimen dimensions was intended to observe the influence of material size on the cooling rate during the thermal cycle simulation.

2. Equipment and Instruments

The equipment and measuring instruments used in this study included:

- Electric furnace for controlled heating of specimens to predetermined peak temperatures.
- Thermocouple temperature sensor for measuring specimen temperature during cooling.
- Temperature data logger / data acquisition system for recording temperature changes over time.
- Stopwatch for monitoring cooling duration.

- Vernier caliper for measuring specimen dimensions.
- Protective equipment (heat-resistant gloves, tongs, safety glasses) for safe specimen handling.

3. Experimental Procedure

The experimental procedure consisted of the following steps:

a. Specimen Preparation

AISI 1015 steel specimens were machined according to the specified dimensions. Surface cleaning was performed to remove rust, oil, and contaminants that might affect heat transfer during testing.

b. Heat Treatment Process

Each specimen was heated in an electric furnace until reaching the designated peak temperature. Four peak temperature variations were applied:

- 750°C
- 800°C
- 900°C
- 1000°C

The specimen was held at the target temperature for sufficient time to ensure uniform heat distribution throughout the material.

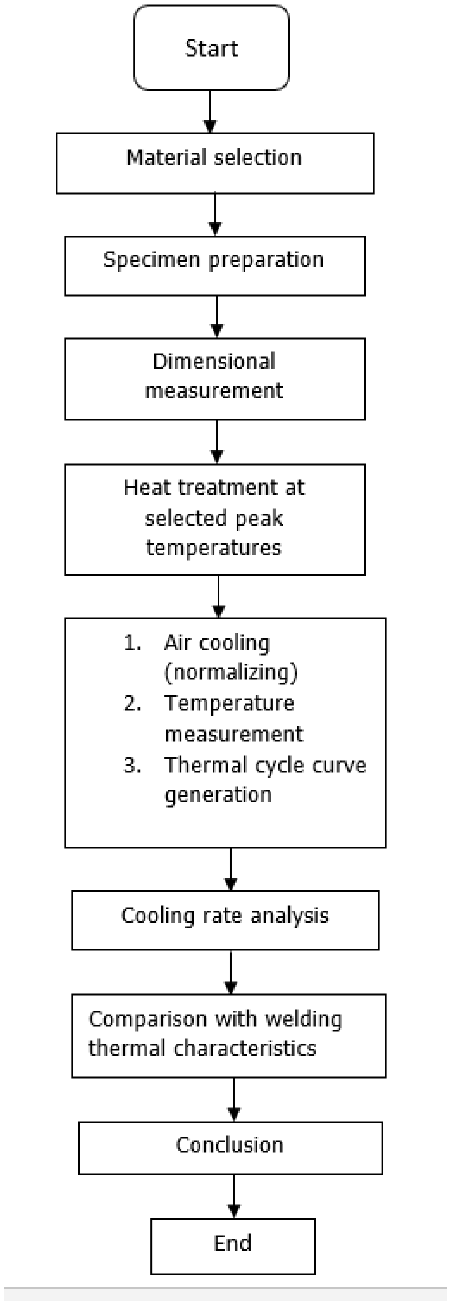
c. Cooling Process

After reaching the peak temperature, the specimen was removed from the furnace and cooled naturally in free air (normalizing process**)**. Temperature changes during cooling were continuously measured using thermocouples.

d. Data Collection

Temperature data were recorded as a function of time to generate thermal cycle curves for each specimen. Cooling rates were determined from the slope of the temperature-time curves.

This study follows the research flow diagram shown below.



Results and Discussion

Research Data and Results Analysis

1. Experimental Data

The thermal cycle simulation test was conducted on AISI 1015 low-carbon steel specimens using the heat treatment (normalizing) method with variations in peak temperature. Temperature changes during cooling were recorded to determine the cooling characteristics of each specimen

Table 1. Cooling Time Data for Large Specimen (100 × 20 × 20 mm)

Peak Temperature (°C)	Time to Reach 600°C (s)	Time to Reach 400°C (s)	Time to Reach 200°C (s)	Average Cooling Rate (°C/s)
750	85	190	420	1.31
800	95	215	465	1.29
900	115	255	540	1.30
1000	140	315	650	1.23

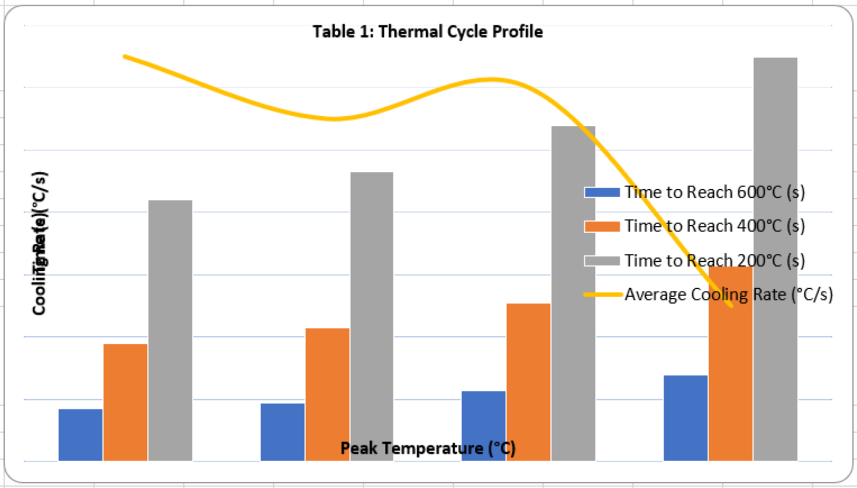


Figure 1. Grafik Cooling Time Data for Large Specimen

Table 2. Cooling Time Data for Small Specimen (50 × 20 × 20 mm)

Peak Temperature (°C)	Time to Reach 600°C (s)	Time to Reach 400°C (s)	Time to Reach 200°C (s)	Average Cooling Rate (°C/s)
750	52	120	260	2.12
800	60	138	295	2.03
900	75	170	360	1.94
1000	92	205	430	1.86

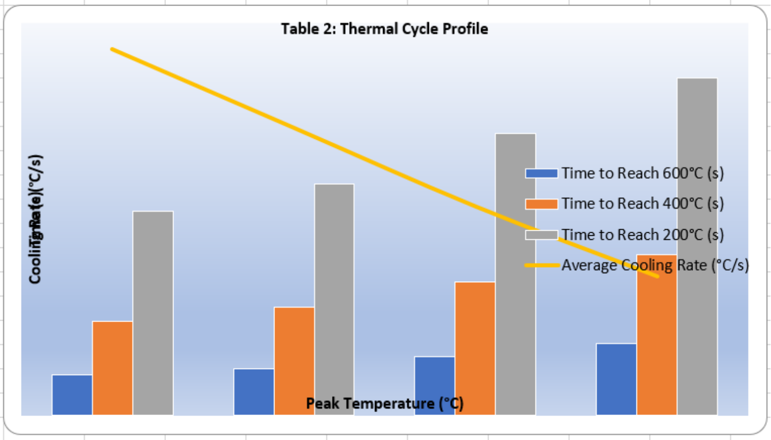


Figure 2. Grafik Cooling Time Data for Large Specimen

2. Thermal Cycle Curve Characteristics

The experimental results indicate that increasing peak temperature leads to longer cooling times for both specimen sizes. This occurs because a greater amount of thermal energy is stored in the material at higher temperatures, requiring more time for heat dissipation into the surrounding air.

The smaller specimen exhibited significantly faster cooling compared to the larger specimen. This behavior is attributed to the smaller thermal mass and larger surface-area-to-volume ratio, which enhances convective heat transfer

3. Cooling Rate Analysis

For the large specimen, the average cooling rate ranged from **1.23–1.31 °C/s**, while the small specimen showed cooling rates between **1.86–2.12 °C/s**.

These results demonstrate that specimen geometry strongly influences cooling behavior. Smaller specimens cool more rapidly due to reduced heat retention capacity.

When compared to actual welding thermal cycles, the simulated heat treatment cooling behavior differs considerably. In welding, cooling occurs under localized moving heat input, producing steep thermal gradients and rapid cooling near the weld zone.

In contrast, the heat treatment process applies uniform heating across the specimen followed by natural cooling, resulting in slower and more homogeneous heat dissipation.

Conclusion

Based on the experimental results of thermal cycle simulation using the heat treatment (*normalizing*) method on AISI 1015 low-carbon steel, several conclusions can be drawn.

First, the peak temperature significantly affected the cooling behavior of the specimens. Higher peak temperatures resulted in longer cooling times because the material stored greater thermal energy, requiring a longer period for heat dissipation into the surrounding environment.

Second, specimen dimensions had a considerable influence on the cooling rate. The smaller specimen (50 × 20 × 20 mm) exhibited a faster cooling rate compared to the larger specimen (100 × 20 × 20 mm). This phenomenon occurred due to the higher surface-area-to-volume ratio of the smaller specimen, which enhanced heat transfer to the surrounding air.

Third, the thermal cycle curves obtained from the heat treatment process showed a relatively gradual and uniform cooling pattern. In contrast, the actual welding process typically produces rapid localized heating followed by steep cooling due to the movement of the heat source and concentrated thermal input.

Finally, the comparison between the simulated thermal cycle and actual welding characteristics indicates that the heat treatment method using the normalizing process cannot accurately represent the real thermal cycle of welding. Therefore, the use of conventional heat treatment as an alternative method for determining welding thermal cycles is **not recommended**, particularly when accurate thermal behavior representation is required for welding analysis

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