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Research Article

A Comprehensive Study of the Relationships between Hardenability and Heat Transfer in a Jominy Test Sample

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Abstract : Quenching is that the steel is quickly cooled in a quenching medium from the austenetising temperature, typically in between 845 and 870 ^0C. Jominy end quench test is a standard test used to characterize hardenability of steels. In this study, 1050 steel is quenched with Jominy end quenched test. Thermocouples were placed on the sample to determine the cooling rate in Jominy sample quenched end, and is investigated the relationship between heat transfer and hardenability. The relations among critical cooling rate, heat transfer and hardness is determinated in Jominy sample for 1050 steel. At the point where the maximum hardness was observed that the maximum cooling rate. Heat transfer quantitative is fastest in 790 ^0C. This point of temperature is determinated that critical a value for hardenability of 1050 steel.

Keywords : Jominy quenched end test, Hardenability, Hardness and heat transfer.

1 Introduction

The Jominy quenching method is a standard test used to determine the hardenability of steels. In this method, a cylindrical sample, 100 mm in length and 25 mm in diameter, is heated to the austenitizing temperature and cooled by applying pressurized water to the end of the sample [1].

Quenching refers to the process of rapidly cooling steel from the austenitizing temperature, which is typically between 845–870 ^0C, in a quenching medium. This process prevents the formation of ferrite or pearlite during phase transformation and aims for the formation of bainite or martensite instead, [2]- [3]. The tendency of a steel to form martensite, leading to an increase in hardness, is referred to as its hardenability. Carbon content and the cooling rate are critical factors for achieving the maximum attainable hardness under normal conditions [4]. Numerous studies have focused on the relationship between the characteristics of the quenching medium [5]- [6]- [7], the specimen [8]- [9], and the heat transfer during the quenching process [10], [11], [12], [13], [14].

In addition to the Jominy test, numerical prediction methods for hardenability are also found in the literature. Even a rough estimate of the cooling intensity can be highly beneficial, as it can be used to determine the quenching response of various types of steel with different compositions and sizes [15]. Numerous studies have particularly focused on the prediction of hardness through numerical calculations in the Jominy quenching test.

The hardenability of a steel sample can be predicted using numerical heat transfer models, provided that the thermal properties of the sample are known [16] , [**?**]. A cylindrical Jominy specimen, 100 mm in length and 25 mm in diameter, was heated to 900 ^0C and subjected to water jet quenching using the Iterative Regularization Method (IRM) and Function Specification Method (FSM) to investigate the hardness change as a function of heat transfer coefficient variation. In this process, the relationship between heat transfer and the boiling and evaporation stages of water was examined, along with the microstructural changes in the material [17]. In another study, where two thermocouples were placed at depths of 1.3 mm from the surface, 10 mm, and 50 mm from the end of the specimen, cooling rates were measured. The effect of cooling rate on the material's microstructure at critical temperatures was analyzed, exploring how the quenching conditions affected the formation of microstructures [11]. For examining the effects of variations in the Jominy quenching conditions on hardenability, a mixture of air and water was used for quenching, and it was observed that hardness values at the first 10 mm distance were higher than those obtained with normal pressurized water [18]. There is an inevitable relationship between the quenching medium and heat transfer coefficient in terms of hardenability [17]. Specifically, during the Jominy test, the specimen is cooled from only one

Table 1: Chemical Composition of AISI 1050 Steel (%)

C	Mn	Si	P	S	Cr	Mo	Ni	Al	Cu	Sn	Fe
0.50	0.64	0.24	0.010	0.005	0.12	0.01	0.07	0.014	0.16	0.011	98.22

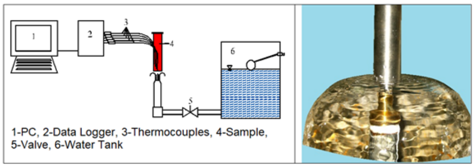

Figure 1: Jominy Quenching Test and Cooling System

end, and the relationship between heat transfer at that end and hardenability is significant. These relationships can be explored through both numerical calculations and experimental studies.

In this study, the Jominy quenching test was applied to 1050 steel. Thermocouples were placed on the specimen to determine the cooling rate at the quenched end, and the relationship between hardenability and heat transfer at the quenching end was investigated. The variation of the heat transfer coefficient with temperature and time was determined, and the effects of heat transfer events at the quenching end on hardenability were analyzed.

2 Experimental Study

The specimens, prepared in accordance with the TS 1381 EN ISO 642 standard (100 mm in length and 25 mm in diameter), were heated to 840 ^0C in a heat treatment furnace and quenched in water at a pressure of 65 $mmSS$ using the cooling system shown in Figure 1. The temperature data, recorded over time from thermocouples placed at 1 mm from the quenching end and at distances of 5 mm and 10 mm, were transferred to a data acquisition card [19].

After being ground to a thickness of 0.4 mm axially, the Rockwell C hardness values were measured to determine the hardness depth of the specimens.

For optical microscopy, the samples were sequentially polished with SiC abrasive papers of 400, 600, and 1200 grit, followed by polishing with 0.25–1 μm diamond paste. After polishing, the samples were washed with ethyl alcohol and dried. To reveal the microstructure, the specimens were etched using a mixture of 3% nitric acid and 97% ethyl alcohol.

3 Results and Discussion

The experimental results showed the time-dependent cooling curves, as measured by K-type thermocouples at the quenched end, 5 mm, and 10 mm from the quenching surface, which are presented in Figure 2. Continuous cooling curves for the Jominy sample were measured using these thermocouples.

In Figure 2, as the cooling proceeds from the quenched end towards the interior of the sample, the cooling rate decreases over time. Notably, at 10 mm, the transformation to ferrite and bainite is observed. In contrast, at the quenched end, a lower cooling rate than the critical cooling curve was achieved, and the structure was fully martensitic. This difference is evident in the hardness values as well. At 5 mm, the structure contains a mix of bainite and a small amount of ferrite, with a hardness value of 53 HRC, which indicates that the majority of the structure is martensitic. The microhardness value at this point is much closer to the hardness at the quenched end, which is 61 HRC, than to the hardness at 10 mm, which is 30 HRC.

In the Jominy quenching test, heat loss occurs at the quenched end. The time-dependent variation of the heat transfer coefficient (h) at a pressure of 65 $mmSS$ is shown in Figure 3, and its variation with temperature is shown in Figure 4.

At 65 $mmSS$ pressure during the Jominy test, the heat transfer coefficient at the quenched end continuously increased until 2 seconds, reaching 11200 W/m²°C. From 2 to 5 seconds, a continuous decrease was observed, reaching 2300 $W/m^{20}C$at 5 seconds. After this point, the heat transfer coefficient showed little change, following a downward trend over time.

A study examining the variation of the heat transfer coefficient with time and distance from the quenched end found that the heat transfer rate was maximum in the first 2 seconds, after which it decreased linearly [10]. This finding is consistent with the result in this study, where the heat transfer coefficient reached its maximum at 2 seconds.

The specimen reached 11200 $W/m^2\ ^0C$ at 790 ^0C. Figure 4 shows that during cooling, the heat transfer coefficient rapidly increased to 11200 $W/m^{20}C$ at 790 ^0C. As cooling continued to 430 ^0C, the heat transfer coefficient decreased linearly to 2300 $W/m^{20}C$. An increase was observed up to 385 ^0C, reaching 3000 $W/m^{20}C$, after which a continuous decrease occurred until the cooling medium temperature was reached. These temperature points correspond to critical temperature points during cooling and can be associated with hardenability. Particularly, temperatures between 700–800 ^0C, corresponding to the 2nd second of quenching, are directly related to hardenability [11].

As expected, the amount of heat transferred is inversely proportional to the variation of the heat transfer coefficient. The changes in the amount of transferred heat over time and with temperature are shown in Figures 5 and 6, respectively.

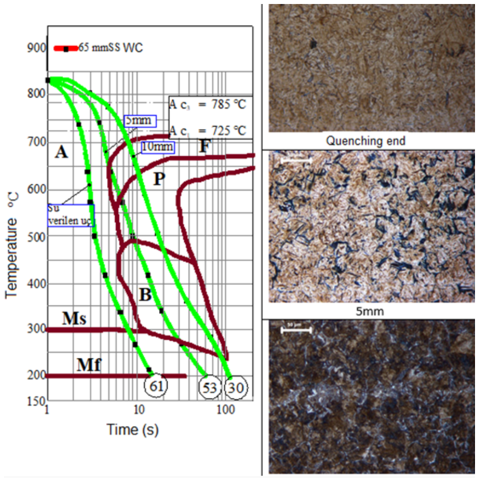

Figure 2: Jominy quenching end, cooling curves, hardness values and microstructure photographs at 5mm and 10mm distances.

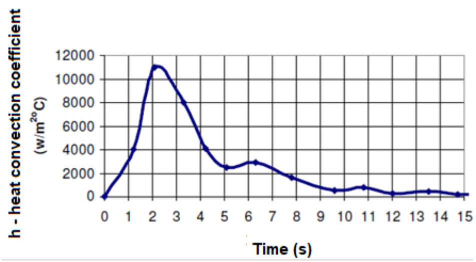

Figure 3: Time-dependent variation of the heat transfer coefficient at the quenching end.

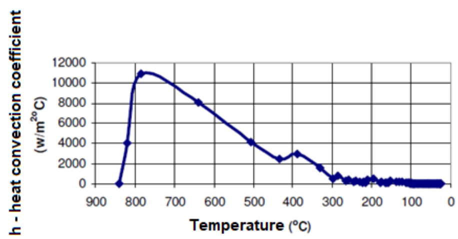

Figure 4: Variation of the heat transfer coefficient with temperature at the quenching end.

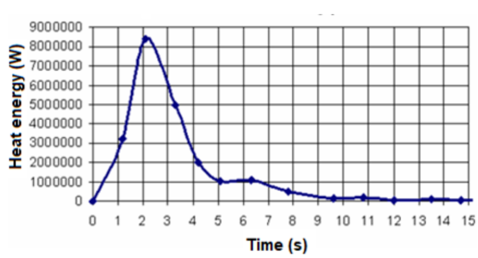

Figure 5: Time-dependent change in energy transferred from the quenching end.

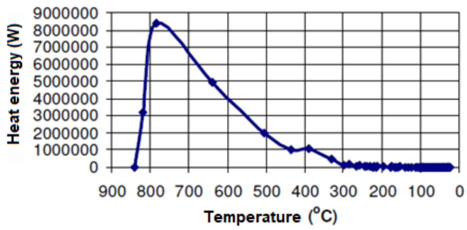

Figure 6: Temperature-dependent change in energy transferred from the quenching end.

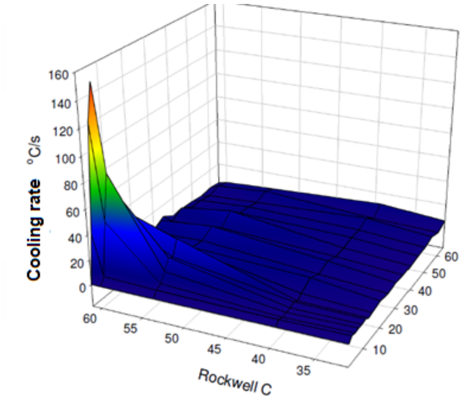

Figure 7: Change of hardness and cooling rate with distance from the end at 65 mmSS Pressure.

In Figure 5, the change in transferred heat over time shows a rapid increase in the first 2 seconds, reaching a value of $8x10^6$ W. After this point, a decrease is observed until 5 seconds, and the transferred heat energy dropped to 10^6 W.

As for the temperature-dependent heat transfer, energy was mainly transferred at temperatures above 800 ^0C during the initial stages. The highest heat transfer occurred at 790 ^0C, after which the amount of energy transferred began to decrease as the cooling continued. Thus, the maximum energy transfer occurred at the highest temperature range, which also relates to the hardenability of the steel. Lower transfer rates below 500 ^0C led to lower martensitic phase formation at the interior points of the specimen, which explains the difference in hardness measured from the quenched end to the interior.

The Figure 7 is given so that the cooling rate and hardness relationship of the Jominy test sample, especially at the tip, at 5 mm and 10 mm distance can be shown in more detail in 3D.

The maximum cooling rate is 145 $^0C/s$ versus 61 HRC hardness the end surface of sample. The cooling rates at 5 mm and 10 mm distances are 80 $^0C/s$ and 40 $^0C/s$, respectively, and the efficiency values are 53 HRC and 30 HRC. As can be seen from the figure, the efficiency values are not change a lot after 10 mm, and in the same way, the cooling rate of the experimental result does not change much after 10 mm.

4 Conclusion

The results of this study show a clear correlation between the cooling rate, heat transfer coefficient, and hardenability of AISI 1050 steel during the Jominy quenching test.

The cooling rate is highest at the quenched end, resulting in a fully martensitic microstructure and the highest hardness. As the distance from the quenched end increases, the cooling rate decreases, leading to the formation of bainite and ferrite, which corresponds to a decrease in hardness. The heat transfer coefficient was found to be temperature-dependent, with higher values observed in the initial cooling stages. The critical cooling rate for hardenability corresponds with temperatures in the range of 700–800 ^0C, where the highest heat transfer rates are observed. Therefore, controlling quenching conditions and understanding the heat transfer behavior are essential for optimizing the hardenability of steels.

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Authors' Contributions

In this study, MÇ performed this work and wrote up the article.

Competing Interests

The authors declare that they have no conflict of interest.

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