Study on Heat Transfer Phenomena in Quenching of Steel*

(Effect of latent heat of phase transformation)

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The effects of the heat transfer and the generated latent heat of phase transformation on the heat treatment of carbon steel (quenching) are studied analytically and experimentally. The effects of the heat transfer and the latent heat of phase transformation on the results of quenching are found not so simple as generally expected. Thus far, the cooling rate has not yet been exactly defined. Using the instantaneous cooling rate at the A_1 point it is shown that this cooling rate has the most important effect on the microstructure and the hardness of the quenched steel.

Key Words : Latent Heat of Phase Transformation, Thermal Conduction, Cooling Rate, Hardness of Steel, Quenching

1. Introduction

In order to impart carbon steel with appropriate hardness and other necessary mechanical properties, we utilize the quenching method. Results of the quenching are strongly influenced by heat conduction in the steel and boiling heat transfer between the steel surface and the cooling liquid (coolant). In former studies about quenching, the research was mainly concerned with the transient boiling heat transfer⁽¹⁾⁽¹⁰⁾ or the unsteady heat conduction.⁽¹¹⁾⁽²⁰⁾ We generally use the hardness obtained after the quenching as the effectiveness grade of quenching. The kind of coolant and the cooling method (subcooling, flow condition and types of spray injection of coolant) have direct effects upon the hardness obtained. The change of microstructure in the steel affects the hardness and the behaviour of the latent heat of phase transformation (hereafter called the latent heat), and plays an important role in the hardening process, too. Only a few papers about latent heat problems have so far been written. Davis⁽¹¹⁾ reported the results of cooling curves about the latent heat. Under the assumptions that free energy is a liner function of temperature and the surface heat transfer coefficient is constant, he examined the relations between experimental and calculated cooling curves using the finite difference method. Inoue⁽¹⁴⁾ and Kishino⁽¹⁷⁾, et al. reported on the problems of quenching with heat conduction and elasto-plastic stresses.

They compared the results between experimental and calculated cooling curves using the finite element method. However, in these reports, though it is known that the cooling curves are affected by the latent heat, no one has actually studied the phenomena until now.

The purpose of this study is to make clear the phase transformation phenomena through an analysis of heat transfer during the quenching. We obtain the latent heat through the analysis of the cooling curves and compare it with the hardness or the microstructure of a quenched carbon steel.

Hitherto we have used a cooling rate to express the degree of phase transformation for the quenching. However, we have a multiplicity of definitions for the cooling rate, for example the cooling rate at 700 °C or 720 °C and mean cooling rate from 700 to 500 °C, or from 800 to 600 °C. Although all these definitions should have their own merits or demerits, in this report we take the instantaneous cooling rate at 727 °C of the A_1 point⁽²¹⁾ and hereafter call it the A_1 cooling rate.

The material of the specimen is S45C carbon steel that is used in large amounts as quenched parts such as bolts, push rods, cam shafts, etc. The dimensions of the specimen are listed in Table 2. The specimen is heated by an electric furnace containing nitrogen gas, which prevents the oxidation of the surface of the specimen. We use city water once heated up to boiling point before the quenching.

The purposes of the present test on the phase transformation phenomena are as follows:

(1) The initial temperature of the specimen is kept above and also below the A_1 point temperature at different times. We compare the calculated values using the finite difference method with the experimental values of the cooling curves. Thus we are able to clarify the effects of the latent heat.

(2) We present a measuring method

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Fig.2 The dimensions and the locations of the thermocouple of the cylindrical specimen

Fig.3 Experimental cooling curves for the same radius of cylindrical specimen

with the theoretical values which had been calculated by the finite difference method

$$\frac{\partial}{\partial R} \left(\lambda \frac{\partial T}{\partial R} \right) + \frac{1}{R} \left(\lambda \frac{\partial T}{\partial R} \right) + \dot{E}_g = \rho c \frac{\partial T}{\partial t} \quad \dots (1)$$

$\dot{E}_g$ of the third term on the left side of the equation (1) is the generated heat of phase transformation. The initial conditions were taken as a quadratic function of the initial temperature. The boundary conditions used to measure the temperature of the R1 point are shown in Fig.2. The thermal conductivity λ and the heat capacity c were taken as quadratic functions of the temperature due to the analysis of the regression equation of the values of literature.^(22,23) The density ρ is assumed as constant because the surface of the specimen cools very fast during the quenching and the variation of its volume due to expansion during the quenching is very small. The cooling curves were calculated using an iterative technique of implicit finite difference. The number of the finite radial elements is $n=10$ and the interval is $t=0.1s$.

As equation (1) is one dimensional in terms of the radius, we examined it in order to check the experimental procedure. Figure 3 shows the experimental cooling curves for the same radius of a $\phi 30mm$ specimen. Figure 3(a) shows the results of the air and Fig. 3(b) those of nitrogen as the furnace gas, respectively. Comparing Fig. 3(a) and (b), it is seen that the transient temperature at each point has the same values as from the results of Fig. 3(b), and it was cooled uniformly on the same circumference. In view of these results, we adopt the method heating with nitrogen gas.

Figure 4 shows the experimental and calculated cooling curves for the initial temperature of 700 °C. The experimental results are the dotted line and calculated results are the solid line, and the

Fig.4 The experimental and calculated cooling curves for the initial temperature 700 °C (the diameter $D=\phi 30mm$)

Fig.5 The experimental and calculated cooling rate curves for the initial temperature of 700 °C

Fig.6 The experimental and calculated cooling curves for the initial temperature 850 °C (the diameter $D=\phi 30\text{mm}$)

positions from the center of the cylinder are indicated by the symbols R1 to R5. The experimental and calculated cooling curves agreed sufficiently well in spite of a fast change of temperature.

Figure 5 shows the cooling rate curves obtained from the cooling curves of Fig.4. For easier understanding of the effects of the latent heat, we take the ordinate as temperature and the abscissa as logarithm of the cooling rate. The cooling rate distribution gets slower towards the core of the specimen and we obtained the same tendency from the results for R4 and R5.

As mentioned in the above, the experimental cooling curves agreed well with the calculated results using the implicit finite difference, in the case of no latent heat generation.

3.2 The effect of the latent heat on the quenching

As mentioned in the previous chapter, in the case of no latent heat generation, the experimentally measured temperature distribution agreed well with that of theoretical calculation. We assume that this equality is valid in the temperature region higher than the transformation temperature, if the latent heat is not generated. Then using the temperature difference between the actual experimentally measured temperature distribution (latent heat generated) and that of theoretical calculation (no latent heat generation), we study the effects of the latent heat generation, namely the phase transformation.

Figures 6 and 7 show the cooling curves and the cooling rate curves when the initial temperature is 850 °C. If the latent heat isn't generated, the experimental cooling rate curves must be in the same form as in the results in Fig.5. But they are of a complicated distribution. It is evident that the cooling rate curves differ from each other. Comparison between the experimental and calculated results at each position is made in Fig.8 as an example. The part where the cooling rate curves differ is considered to indicate an effect of the latent heat. The

Fig.7 The experimental cooling rate curves for the initial temperature of 850 °C

Fig.8 The comparison between the experimental and calculated cooling rate curves

Fig.9 The range of temperatures in which the phase transformation occurs

relation between the A1 cooling rate and the temperature of phase transformation is shown in Fig.9. It is obvious that the range of temperatures in which the phase transformation occurs is fairly wide within the range of measurements.

3.3 The relationship between the temperature of phase transformation and the A_1 cooling rate

From the discussion of the previous chapters, it is clear that the effect of the latent heat emerges during the quenching. But it is difficult to explain the phase transformation phenomena by the experimental cooling curves on any radius for the following reason.

The cylindrical specimen is divided into the elements as shown in Fig.10 and the heat balances for each element are given in the equation (2)-(4).

$$\text{core element : } \dot{E}_c = Q_{out} + \dot{E}_s \dots\dots\dots(2)$$

$$\text{inner element : } Q_{in} + \dot{E}_c = Q_{out} + \dot{E}_s \dots\dots\dots(3)$$

$$\text{surface element : } Q_{in} + \dot{E}_c = Q_{out} + \dot{E}_s \dots\dots\dots(4)$$

Fig.10 The elements of the cylindrical coordinates

Fig.11 The experimental cooling curves at the center (the effect of the diameter)

Fig.12 The experimental cooling rate curves at the center (the effect of the diameter)

The equation for the core element has only a generation term $\dot{E}_c$ and doesn't have a term for the heat flow Q_{in} . The generation term $\dot{E}_c$ is the sum of Q_{out} and $\dot{E}_s$. In case of the inner element and surface element, the generation term $\dot{E}_c$ is very complicated since we must add Q_{in} to it. If we make an experiment concerning the core element that doesn't have $\dot{E}_c$, we are able to examine the latent heat a little more easily.

Figure 11 shows the experimental results of the cooling curves at the center of any diameter. It is evident that the larger the diameter the cooling time becomes longer, and the effect of the latent heat becomes clear.

The feature of the temperature range of phase transformation is extremely clear from the cooling rate curves as shown in Fig.12. Namely, the cooling rate curves can be classified into three different types. The first of them is the result obtained by the specimen of large diameter in which occurs a transformation in a range of temperatures between 600 and 650 °C. The second is the result of the small specimen in which occurs a transformation at a low temperature of about 310 °C. The third is the result of the specimens from 16 to 24mm. It has two transformation ranges at different temperatures, so it is called "a split transformation".

The relation between the temperatures of phase transformation and the cooling rates⁽²⁴⁾ is shown in Fig.13. The range of temperatures is a hatched part in which the phase transformation occurs and the temperature at which the phase transformation occurs is indicated with O and ●. The temperature for Ar' transformation has a linear downward curve to 120 °C/s at the A_1 cooling rate. On the other hand, the temperature for Ar'' transformation has a constant value of 310 °C.

3.4 The latent heat of phase transformation

Figure 14 is an illustration of cooling curves and cooling rate curves which show the effects of latent heat

Fig.13 The relation between the temperatures of phase transformation and the A_1 cooling rates

generated by phase transformation on the temperature change of the material (model). In this figure, the solid line indicates a model which generates the latent heat and the fine line indicates a model which doesn't generated the latent heat.

We calculated the latent heat by the following method. In the model for cooling rate curves, the start of the phase transformation is set at point *b* from which it separates into two directions, and the end of the phase transformation is set at point *e* at which the two lines meet again. The time of the phase transformation is a difference between t_e and t_b . It may be considered that the phase transformation occurs concentratedly at the temperature of point *n*. The heat capacity value and the cooling rate value are determined at point *n*. Assuming that a sensible heat from the temperature T_e to T_b is uniformly released at the cooling rate for point *n*, the latent heat q (kJ/kg) can be derived from the equation (5).

$$q = C_n \left[(t_e - t_b) \frac{\Delta T_n}{\Delta t} - (T_b - T_e) \right] \dots \dots (5)$$

Fig.14 The models of the cooling curves and the cooling rate curves for the calculation of the latent heat

Fig.15 The relation between the latent heats of the phase transformation and the A_1 cooling rates

The specific heat and conditions of the calculations have the same values as in chapter 3.1.

The relation between the latent heat and the A_1 cooling rate obtained is shown in Fig.15. The latent heat of Ar' transformation is indicated by the symbol $\diamond$ and the one for Ar'' by the symbol $\circ$ and the one for $Ar'+Ar''$ by the symbol $\bullet$, and the values of the literature⁽²⁵⁾ are marked by the dashed line.

There is a correlation between the latent heat and the temperature of phase transformation in Fig.13. The pearlite transformation is an Ar' transformation and has a constant value of the latent heat. The split type transformation that contains a troostite and a martensite rapidly decreases with the Ar' transformation and increases with the Ar'' transformation in proportion to an increase of the A_1 cooling rate. As a result, the sum of their latent heat decreases in proportion to the A_1 cooling rate. The martensite transformation is only an Ar'' transformation and has a constant value of the latent heat. According to the literature the latent heat of the martensite transformation is of a larger quantity than that of the pearlite transformation.

Fig.16 The microstructures under the effect of A_1 cooling rate

Fig.17 The relation between the hardnesses and the A_1 cooling rates

However, the martensite transformation is a diffusionless reaction and depends on the deformation of the crystal lattice and the supersaturated solid solution. For this reason, it seems more appropriate to consider that the energy release of the martensite transformation is a small quantity as compared with the pearlite transformation. It is concluded that the phenomena of the latent heat can be explained sufficiently by these results.

3.5 The latent heat and hardness

Figure 17 shows the relations between the hardness of the S45C specimen and the A_1 cooling rate. This is the result of the quenching when the initial temperature is 850 °C and the coolant temperature is 20 °C. The central hardnesses for different diameters are shown by the symbol $\bigcirc$ and the cross sectional hardnesses of $\phi 30$ mm by the symbol $\diamond$, and these results are measurements by the micro-Vickers hardness tester. The surface hardnesses of $\phi 6$ mm for different coolant temperatures are shown by the symbol $\diamond$ and they are measurement by the Rockwell hardness tester. The hardnesses of any specimen before the tests were put on the 0 °C/s axis of the A_1 cooling rate. The values of the central and cross sectional hardnesses increase proportionally to A_1 cooling rate from 60 °C/s to 140 °C/s and their increase is less at above 140 °C/s. The results of these hardness and surface hardness tests approximately agree qualitatively. But, the absolute quantities for any A_1 cooling rate are slightly different depending on the tester. It is evident that the hardnesses obtained under the different conditions of the specimen can be arranged by the A_1 cooling rate.

The microstructures under the effect of the A_1 cooling rate are shown in Fig.16. The fine microstructure is a martensite and the black corrosive structure is a troostite. It is clear that the martensite increases rapidly in proportion to the A_1 cooling rate and then in the range over 155 °C/s increases very slowly. The values of the hardnesses increase proportionally to the increase of the martensite.

When the value of the latent heat is large, the hardness is small and vice versa. Furthermore, the hardness approaches a constant value when the latent heat of Ar transformation approaches a constant value, too.

It is evident that the latent heat is inverse to the hardness and the A_1 cooling rate is very important for the quenching.

4. Conclusions

The specimen material, S45C carbon steel, is widely used. The diameters of specimens are of dimensions from $\phi 6$ to $\phi 30$ mm. The specimens are heated up to 700 °C or 850 °C by the electric furnace which contains nitrogen gas and then are immersed quickly into the water bath at a temperature of 20 °C. The cooling curves for different diameters are measured and

the hardness of the specimen, after the quenching, is also measured.

The relations between the latent heat and the temperature of the phase transformation, the hardness and A_1 cooling rate are experimentally examined. Furthermore, the cooling curves obtained during the quenching are compared with the results of theoretical calculation made by the finite difference method.

The results obtained in this study are as follows:

(1) The initial temperature of the specimen is held at 700 °C, that is below the A_1 point temperature. The experimental cooling curves agreed well with the calculated results.

(2) The relations between the calculated and experimental results are studied when heating temperature is 850 °C, i.e. higher than the A_1 point.

(3) We present a method of measuring the temperature at the core of the cylindrical specimen where the effect of the latent heat of phase transformation most clearly appears.

(4) The latent heat of phase transformations is proportional to the temperature of the Ar' transformation and inverse to the hardness. The cooling rate at the temperature of the A_1 phase transformation is very important in the results of the quenching.

Although the effect of the latent heat of phase transformation in the steel during the quenching is recognized, we must further investigate the problems of the unsteady heat conduction accompanied with the transient boiling heat transfer and the latent heat of phase transformation during the quenching.

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