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Heat transfer coefficient and latent heat of martensite in a medium-carbon steel

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Abstract

In this paper the method used in a recently published paper to measure the latent heat of the martensite transformation during quenching of a steel is analysed. The arrangement of the experiment made it possible to obtain reasonable values for the latent heat of transformation, but cannot be expected to produce reasonable values for the heat transfer coefficient. Improved methods are discussed, including the novel probe design of the present authors.

Introduction

In a recent paper the latent heat of martensite transformation in a medium carbon low alloy steel was determined by monitoring the surface temperature during quenching [1]. This was achieved by comparison of the cooling curve against that obtained from an austenitic stainless steel. In this paper it is shown that latent heat determined by this method is in good agreement with that found by thermodynamic calculation. However, with their method it is not possible to determine the heat transfer coefficient accurately, so we believe it is useful to outline alternative methods.

Probe design

In Ref.[1] the temperature was recorded from a K–type thermocouple attached to the surface half–way along the length of a 10 mm diameter cylindrical steel probe. Readings were taken at intervals of 0.15 s using a multimeter. It is claimed that this configuration is similar to the standard probe specified in Japanese standard JIS–K2242, and that it is necessary to use the inverse method to calculate the heat transfer coefficient from the surface temperature.

The configuration of the cylindrical steel probe with the thermocouple attached to the outside has important differences to the JIS–K2242 probe [2, 3] (see figure 1), in which the thermocouple passes through the material to avoid disturbing the metal–quenchant interface. Inserting the thermocouple with the ceramic tubes through the fluid will disturb the fluid flow causing experimental errors [4]. More significant is that the JIS–K2242 probe is made from silver to minimise the effects of sample size. It is designed for comparison of different quenching oils, which have lower maximum heat transfer coefficient than water. In this configuration the Biot number Bi=0.012 (assuming heat transfer coefficient h=2000 $\mathrm{Wm^{-2}\,K^{-1}}$, k=429 $\mathrm{Wm^{-1}\,K^{-1}}$) and for quenching in water Bi=0.029 or 0.058 with agitation (assuming h=5000 or with agitation h=10000 $\mathrm{Wm^{-2}\,K^{-1}}$) [5]. The Biot number (Bi) is the ratio of the external conductance to internal conductance. The condition $Bi \leq 0.1$ justifies an assumption of uniform temperature within the probe during the cooling process (less than 5% difference). For more accurate determination of heat transfer coefficient Tagaya provided a modification of an additional thermocouple positioned at the centre [6]. In the case of medium–carbon steel probe with 10 mm diameter quenched in water, the Biot number is expected to be around 0.42 (k=30 $\mathrm{Wm^{-1}\,K^{-1}}$), this results in a significant temperature profile inside the probe as can be seen from figure 2. The calculation of temperature profile inside the AISA 4340 probe (Fe-0.41C-0.23Si-0.7Mn-1.65Ni-0.67Cr-0.15Mo Wt%) was performed using a physically based mathematical model using the control volume method, developed recently to simulate the quenching process and to predict the time temperature history. The heat transfer coefficient used in this calculation was as reported by Lee and Lee in Ref.[1] (this can be regarded as a conservative value), the thermal conductivity predicted as a function of temperature using a neural network model of thermal conductivity (figure 3) [7, 8], and the heat capacity estimated as a function of temperature using MTDATA thermodynamic calculation with sgte database [9].

Precise prediction of any quenching simulation model requires knowledge of the boundary condition of the model and the physical properties, a miniature steel quench probe has recently been designed by the current authors to measure the heat transfer coefficient for steels as a function of surface temperature [10, 11]. Both lumped heat capacity method and inverse heat conduction models were utilised in the design of the probe, a probe diameter of 2 mm or below being necessary to meet the condition $Bi \leq 0.1$. Typical experimental results for quenching are shown in figure 4(a), for steel with composition Fe-0.55C-0.22Si-0.77Mn-0.2Cr-0.15Ni-0.05Mo-0.001V Wt%.

Inverse method

During quenching it is not straight–forward to measure the temperature of the interface directly. A useful method is to place thermocouples in the body of the probe and to calculate the temperature at the surface using the inverse method [4, 12, 13, 14]. The 'inverse heat conduction analysis' is usually defined as the estimation of the boundary conditions from transient temperature measurements at one or more interior locations [15, 16].

Use of the inverse method to accurately determine all the heat transfers is not possible using a single thermocouple attached to the outer surface. Instead Lee and Lee measured the temperature at the surface and modelled the heat distribution inside the sample using values of conductivity and heat capacity from the literature [1]. Previous work indicates that attachment of a thermocouple to the outer surface will lead to errors in measuring the heat transfer coefficient, these errors can be eliminated by use of the inverse method with multiple thermocouples to calculate the temperature at the surface in previous studies [17].

The use of two thermocouples one in the centre, and one at or near the surface is also a significant improvement to the use of a single thermocouple at the surface [6, 18].

Thermodynamic calculation

Lee and Lee's analysis is self–consistent and effectively allows the comparison of the cooling curve of a steel which undergoes martensitic transformation to one that does not, and this is why a reasonable value of latent heat has been derived from the experiment. A much simpler analysis should also be possible by directly comparing the cooling curves and considering the specific heat capacity of the two steels.

Thermodynamic software can also be used to calculate the enthalpy change for austenite to ferrite ($\Delta H_{\gamma\rightarrow\alpha}$) as shown in figure 5. The latent heat for transformation to martensite (ΔH_{M}) can then be found by assuming a stored energy in the martensite of 700 $\mathrm{J mol^{-1}}$ [19] and is in good agreement with the value derived by Lee and Lee. Assuming the validity of the Koistinen and Marburger [20] equation to describe the rate of transformation as a function of temperature, it is then possible to calculate the rate of heat release due to the transformation to martensite. The values calculated are compared with the values reported in Ref. [1] in figure 6. The calculation gives a value similar in magnitude to that obtained using the equation from

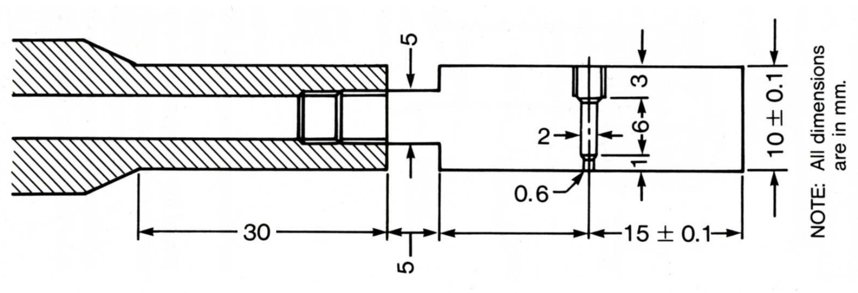

Figure 1: JIS-K2242 silver probe, showing the arrangement of the thermocouple, passing through the probe with junction just below surface.

Ref. [1] (0.041T^2-0.078T-5079.947), but not to the constant value they also proposed (2127.315 Jmol^{-1}). The thermodynamic calculation of the latent heat may be improved by measuring the volume fraction of martensite as a function of temperature, since the Koistinen–Marburger equation is purely empirical, and is known not to apply generally. The temperature distribution inside the probe should also have a significant effect on the experimental measurement.

Conclusions

In summary, it should be possible to measure the latent heat of the martensitic transformation approximately using the method in Ref. [1] since it is effectively comparing the temperature of two similar samples, only one of which exhibits the martensitic transformation. Thermodynamic calculation of the latent heat have been performed and are in broad agreement with the experimental value reported, after taking a value for the energy stored in the martensite microstructure. The methods of calculating the heat transfer coefficient would be improved by alternative probe designs [6, 11, 12].

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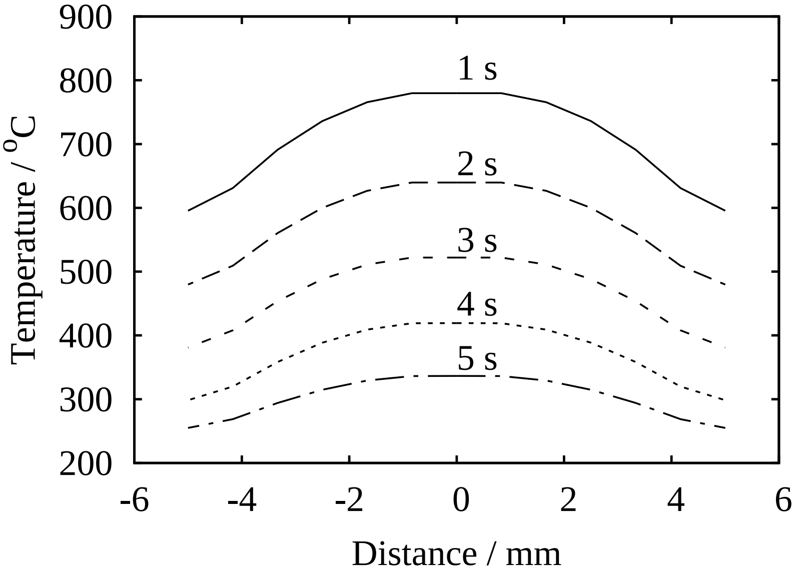


Figure 2: Calculated temperature profile for 4340 steel probe, using heat transfer coefficient reported by Lee and Lee.

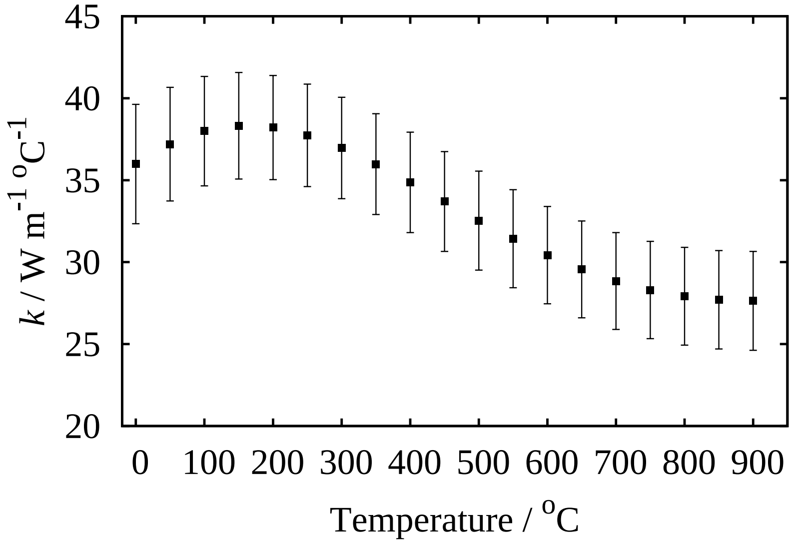
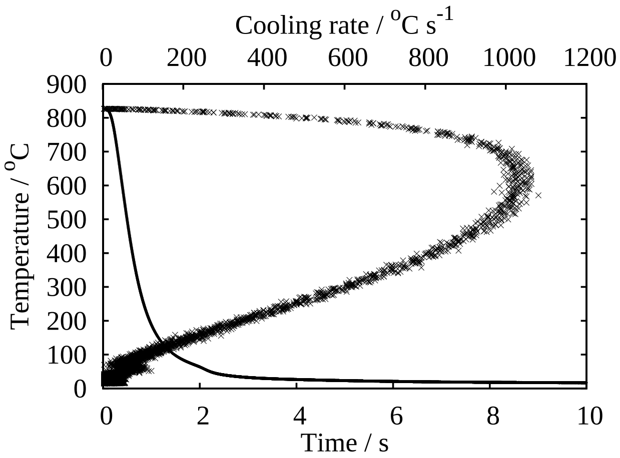
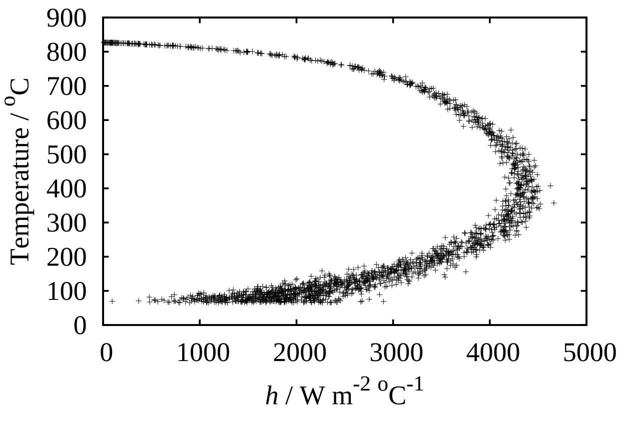


Figure 3: Thermal conductivity, k, for alloy 4340 calculated using a neural network model [8].



(a) Instantaneous temperature and cooling rate



(b) Heat transfer coefficient

Figure 4: Experimental determination of heat transfer coefficient, h, using miniature probe.

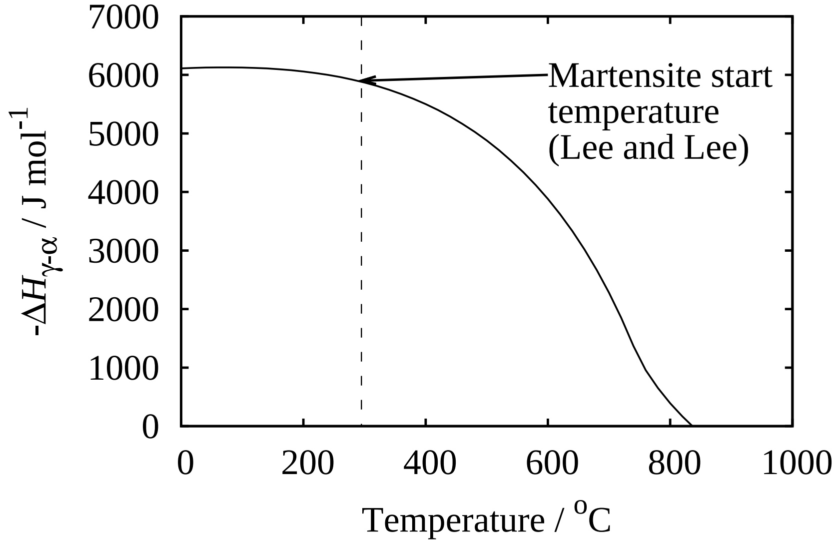


Figure 5: Enthalpy Change for transformation from austenite to ferrite in 4340 steel calculated using mtdata.

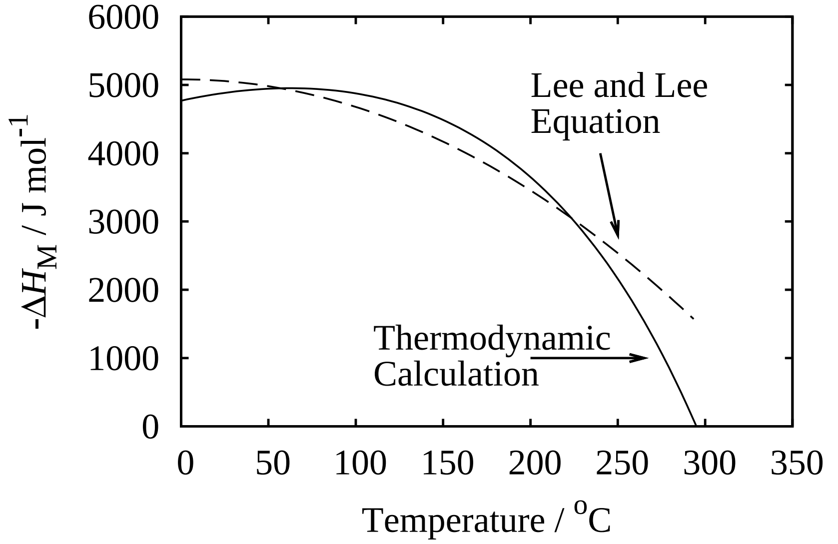


Figure 6: Thermodynamic calculation of latent heat of martensite in alloy 4340 compared to the previously reported value.

References

[1] S-J Lee and Y-K Lee, *Scripta Materialia*, 60:1016–1019, 2009.

[2] Japanese industrial standard K 2242, Heat Treating Oils, 1980.

[3] C. E. Bates, G. E. Tooten, and N. A. Clinton, *Handbook of Quenchants and Quenching Technology.* ASM International, Materials Park, Ohio, 1993.

[4] S. Chantasiriwan, *International Journal of Heat and Mass Transfer*, 27(8):1155–1164, 2000.

[5] C. E. Bates, G. E. Totten and R. L. Brennan, In *ASM Handbook*, vol. 4, pages 67–120, ASM International, Ohio., 1991.

[6] M. Tagaya and I. Tamura, *J. Japan Inst. Metals*, 16:652–655, 1952.

[7] M. J. Peet, H. S. Hasan and H. K. D. H. Bhadeshia, *International Journal of Heat and Mass Transfer*, 54:2602–2608, 2011.

[8] M. J. Peet and H. S. Hasan, MAP STEEL THERMAL 10 *http://www.msm.cam.ac.uk/map/*.

[9] NPL: MTDATA: Software, National Physical Laboratory, Teddington, U.K. (2006).

[10] Hala Salman Hasan, PhD thesis, University of Technology, Baghdad, 2009.

[11] H. S. Hasan, M. Peet, J. M. Jalil, and H. K. D. H. Bhadeshia, *Heat and Mass Transfer*, 47:315–321, 2011

[12] H. M. Park, O. Y. Chung, and J. H. Lee, *International Journal of Heat and Mass Transfer*, 42:127–142, 1999.

[13] D. E. Smith, In *19th ASM Heat treating Society conference proceeding including steel heat treating in the new millennium*, pages 325–333, Materials Park, Ohio. ASM International, 1999.

[14] S. Niu, H. Li, G. Zhao and Y. Luan, *Finite Element in Analysis and Design*, 2006.

[15] C. F. Weber, *International Journal of Heat and Mass Transfer*, 24(11):1783–1792, 1981.

[16] J. Taler and W. Zima, *International Journal of Heat and Mass Transfer*, 42:1123–1140, 1999.

[17] H. K. Kim and S. I. Oh, *Journal of Materials processing Technology*, 112:157–165, 2001.

[18] H. Cheng, J. Xie and J. Li *Computational Materials Science*, 29:453–458, 2004.

[19] J. W. Christian, In *Proceedings of the international conference on martensitic transformations*, Cambridge, Massachusetts, USA, 1979.

[20] D. P. Koistinen and R. E. Marburger, *Acta Metallurgica*, 7:59–60, 1959.