Tempering of Steels

As part of the on-going development of JMatPro, work has been undertaken so that the tempering of steels in the temperature range 200-700ºC can be calculated. In low alloy steels, cementite is the primary hardening phase. In higher alloyed steels cementite is an intermediate phase that is dissolved as stable alloy carbides form. However, the temperature range where the alloy carbides can form is limited as substantial metallic diffusion is required for them to form. Essentially it means that the alloy carbides tend to form only at higher tempering temperatures.

At temperatures below 250°C and for C levels > 0.2%, an intermediate ε-carbide, with a hexagonal crystal structure can form [1]. It has also been postulated that the ε-carbide may be a transitional carbide in the formation of cementite between 200-300ºC, but little concrete evidence exists for this, mainly due to the rapid kinetics of carbide formation in this temperature range. What is well established is that for low alloyed steels between 200-700ºC and medium alloyed steels below 400ºC, it is cementite that provides the strengthening and, as such, only cementite precipitation is considered here.

The aim of the present work is to provide a model that will calculate the strength of tempered martensite as a function of tempering temperature and time. The model considers that precipitation of cementite is so rapid between 200-700ºC that for the current purpose, the initial microstructure can be considered a C-unsaturated form of tempered martensite strengthened by a fine precipitation of cementite. It is further assumed that the precipitate density can be considered essentially constant at this earliest stage. The change in strength on tempering is then mainly due to a coarsening of the cementite precipitates and a softening of the tempered martensite matrix. This means that, for the main part, models already implemented in JMatPro can be utilised.

Cementite particle size during tempering

Coarsening of cementite has been studied in detail by Airey *et al.* [2] Caron and Krauss [3] and Hernandez *et al.* [4]. Calculated results agree well with observation for sizes below 0.4 μm. However, for larger sizes, the calculation appears to overestimate the particle size. It is unclear why such a systematic deviation may occur. However, such large sizes are not produced by "normal" tempering procedures, but occur only after lengthy times (many days) below 650ºC. On that basis, the deviation may be associated with the diffusion of substitutional elements such as Cr and Mn becoming important at long times and high temperatures. It is further noted that, as particle sizes increase to above 0.4μm, there is very little hardening effect anyway. As such, the present calculation is considered quite satisfactory for use in strength calculations for tempered steels. Fig.1 shows the comparison between calculated and observed particle radii at various temperatures and times in the size range 0-0.4μm.

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1. R.W.K. Honeycombe, Steels: Microstructure & Properties, (Edward Arnold, London, 1981).
2. G.P. Airey, T.A. Hughes and R.F. Mehl, Trans.Met.Soc.AIME, 242, (1968), 1583
3. R.N. Caron and G. Krauss, Met.Trans.A, 3, (1972), 2381.
4. V.H. Baltazar Hernandez, S.S. Nayak and Y. Zhou, Met.Mater.Trans.A, 42, (2011), 3115.

Strength of tempered steels

The hardness and/or yield stress of tempered martensitic steels is well documented. Speich [5] measured hardness of steels with C levels varying between 0.026-0.39%C after tempering for 1h between 200-700ºC. Fig. 2 shows the comparison between calculated and observed hardness. The calculation shows both an excellent temperature dependency to the hardness, as well as its variation with C concentration.

The Heat Treater's Guide [6] provides examples of hardness after 2h at the tempering temperature for a wide number of alloy steels, with C content varying from 0.3 to 0.95wt%. Figs.3-5 show comparisons between calculated and experiment for 0.3, 0.4 and 0.5% steels respectively. The results are in good to reasonable agreement.

There are a number of experimental studies of hardness vs time at set temperatures and comparison of calculated result is variable. Figs.6a&b show comparisons of hardness after time at various temperatures for 0.097%C and 0.18%C steels respectively [5]. The agreement here is very good, which is accentuated by the comparison plots between calculated and experimental hardness in Figs.7a&b.

Results are less good for a 0.82%C steel where comparison of hardness after time at various temperatures is shown in Fig.8. Of note is the good agreement after 0.1hrs, but below this time the measured values tend to be significantly lower than calculated.

Overall Comments

The conclusions from the modelling are as follows.

Coarsening appears to be modelled well for usual tempering time/temperature conditions and comparison of tempered hardness in the equivalent time/temperature range appears quite sound. The only concern lies in short tempering times (less than 20 mins as tempering temperatures rise above 300ºC), where hardness may be significantly overestimated.

Future Work

The current model does not yet incorporate a composition dependence for the tempered martensite matrix strength. This may well be required for future work as analysis of the work of Speich who used very high purity Fe, with little or no impurities other than C, shows that the tempered martensite matrix strength is significantly lower than for the more traditional alloyed steels in the Heat Treater's Guide. At present JMatPro incorporates a composition independent strength for the tempered martensite matrix which should be appropriate for low to medium alloyed steels.

At present, the model is not linked with the Simultaneous Precipitation module currently in place within JMatPro. It is planned to link with this at a future stage such that tempering of higher alloyed steels that form alloy carbides can be considered. It is further planned to model the precipitation process of cementite from the initial martensite structure and link this to the Physical and Thermo-Physical models in JMatPro, such that the change in properties over the whole quench and tempering process can be modelled.

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5. G.R. Speich, Trans.Met.Soc.AIME, 245, (1969), 2553.

6 *Heat Treater's Guide: Practices and Procedures for Iron and Steels*, ed. H. Chandler, (ASM international, Materials Park, OH, 1995)

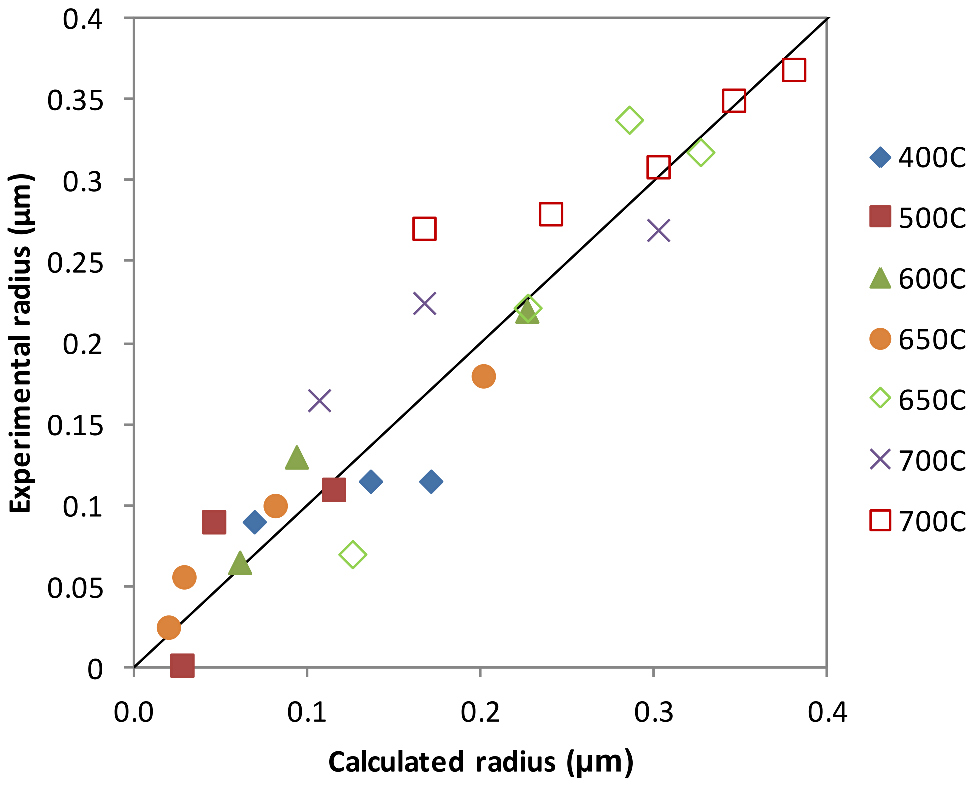


Figure 1. Comparison between calculated and experimentally observed [2,3,4] particle radii of cementite in tempered martensitic steels.

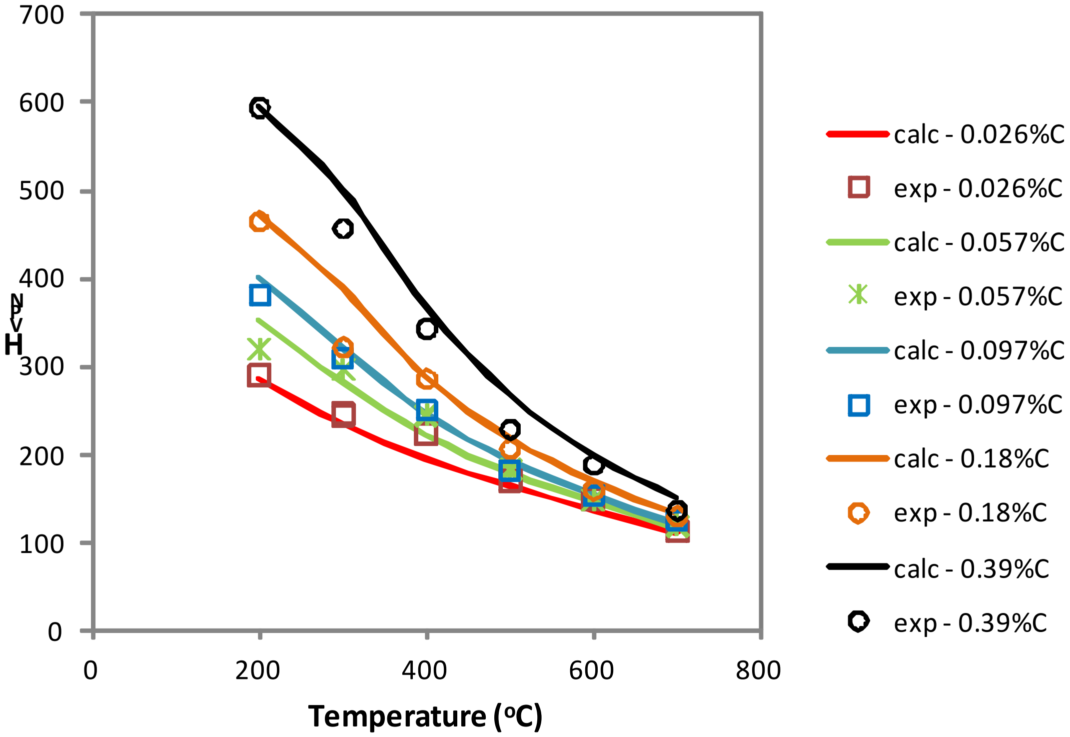


Figure 2. Comparison between calculated and experimentally observed hardness of plain C martensitic steels after tempering for 1 hr at temperature [5].

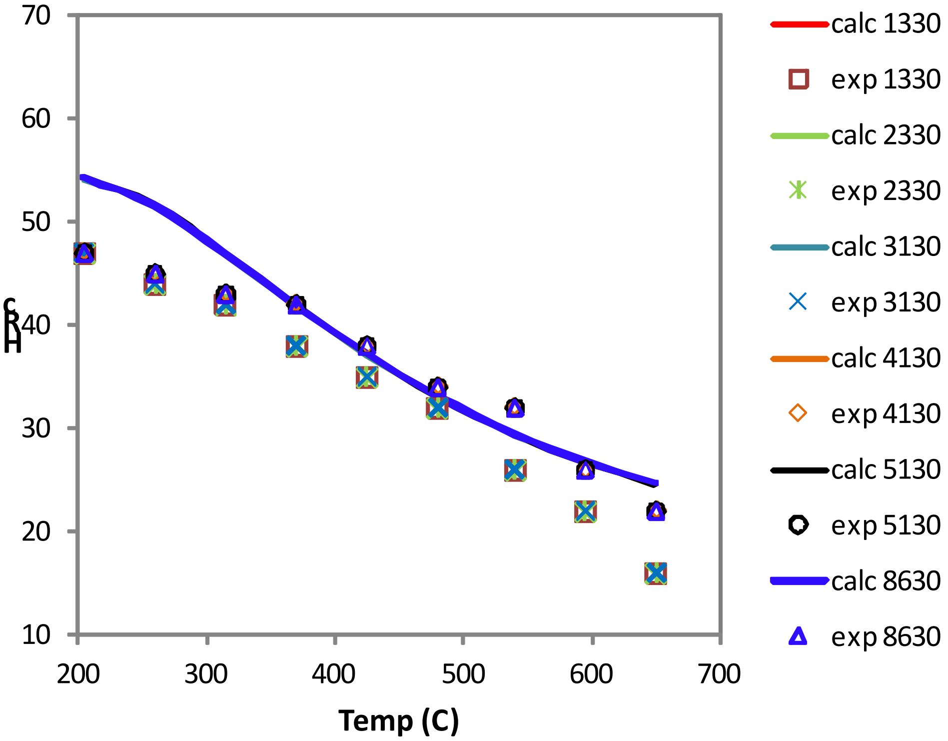


Figure 3. Comparison between calculated and experimentally observed hardness of 0.3%C martensitic alloy steels after tempering for 2 hr at temperature [6].

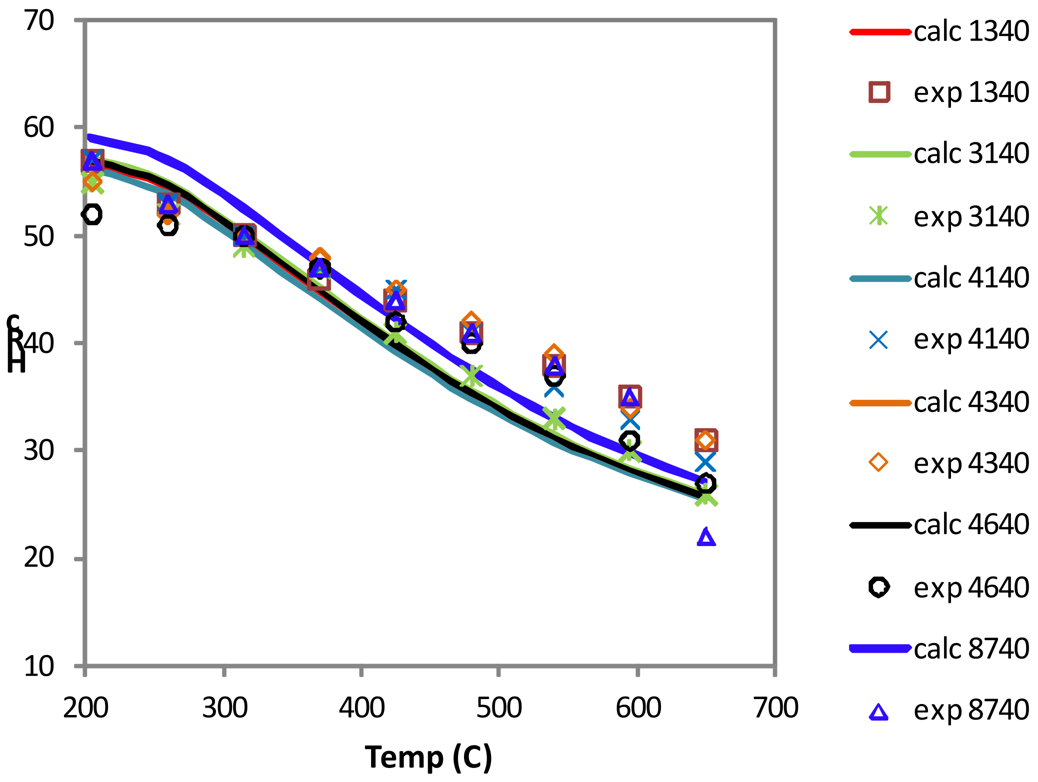


Figure 4. Comparison between calculated and experimentally observed hardness of 0.4%C martensitic alloy steels after tempering for 2 hr at temperature [6].

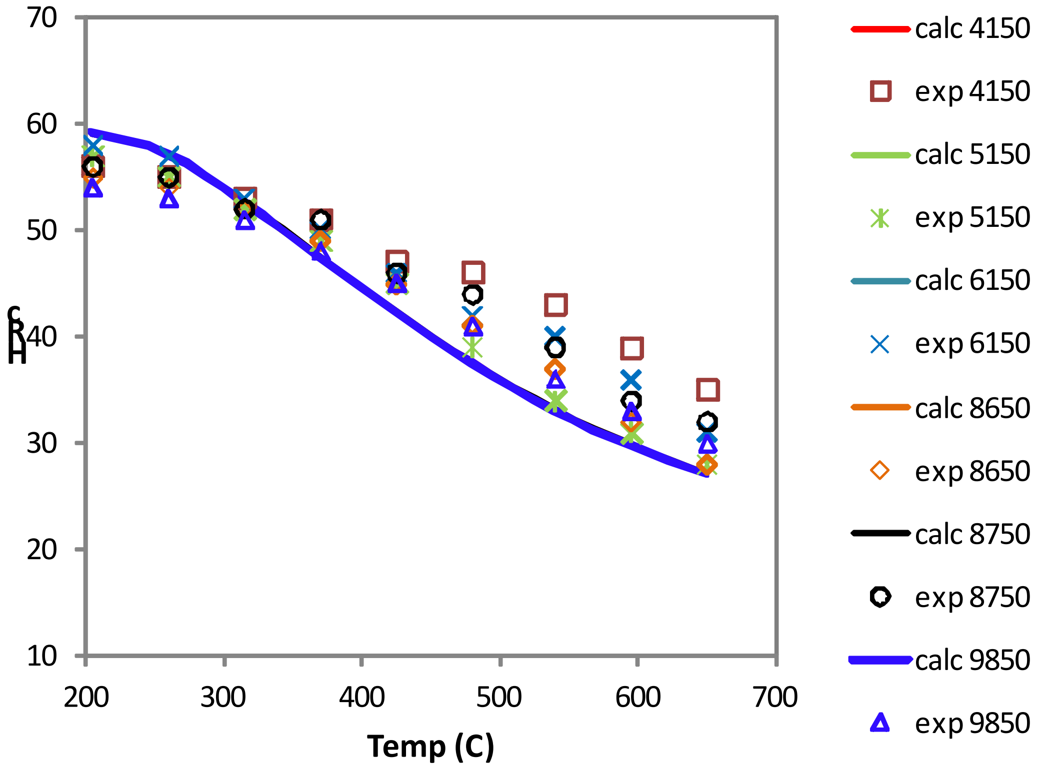


Figure 5. Comparison between calculated and experimentally observed hardness of 0.5%C martensitic alloy steels after tempering for 2 hr at temperature [6].

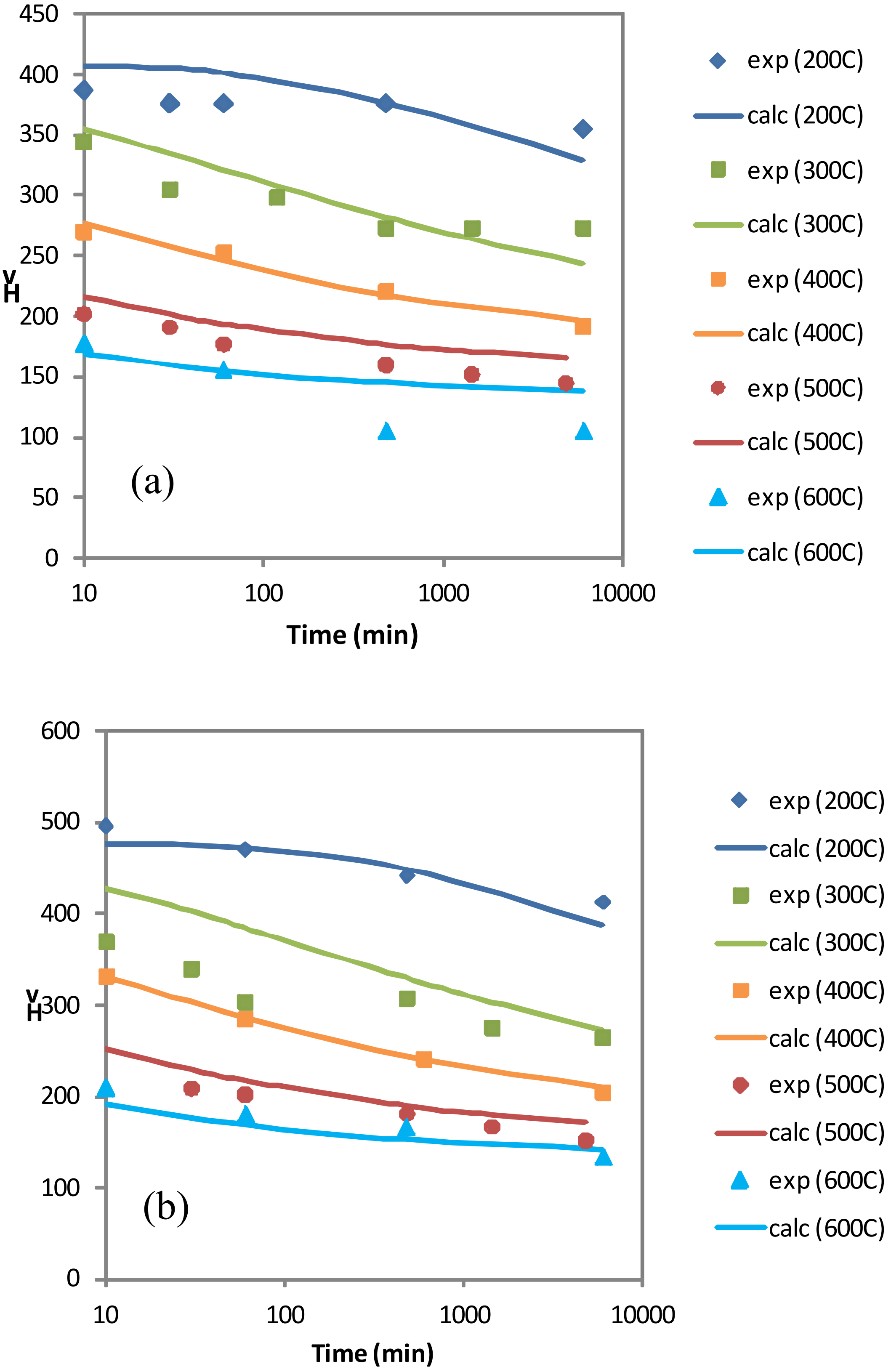
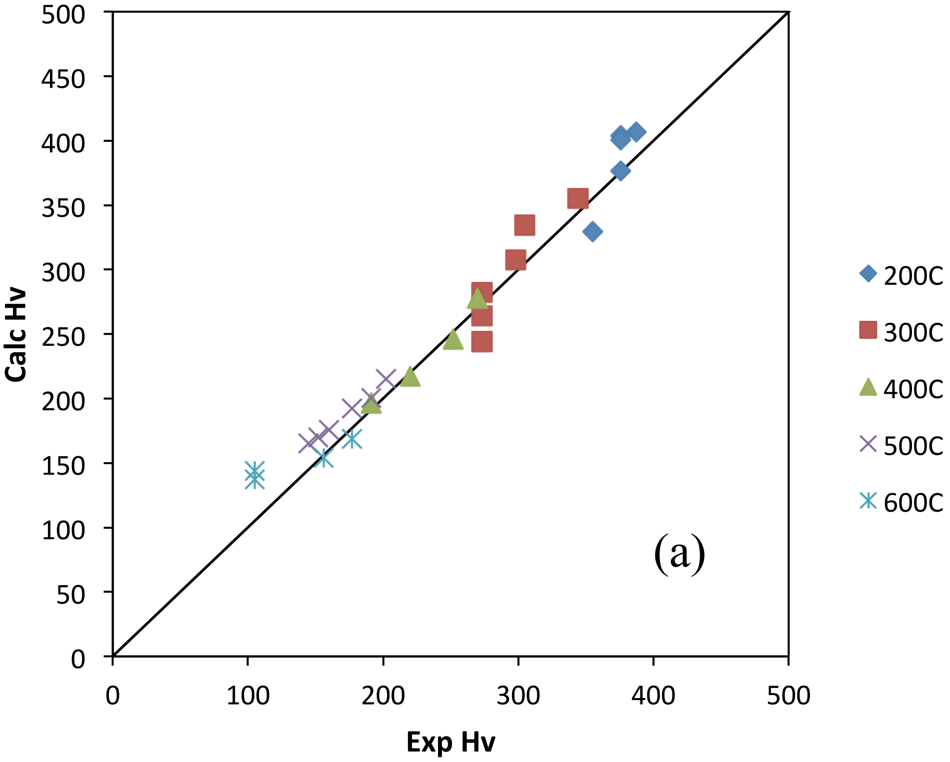


Figure 6. Plots of calculated and experimental [5] hardness vs time for tempered (a) 0.097%C and (b) 0.18%C martensitic steels.



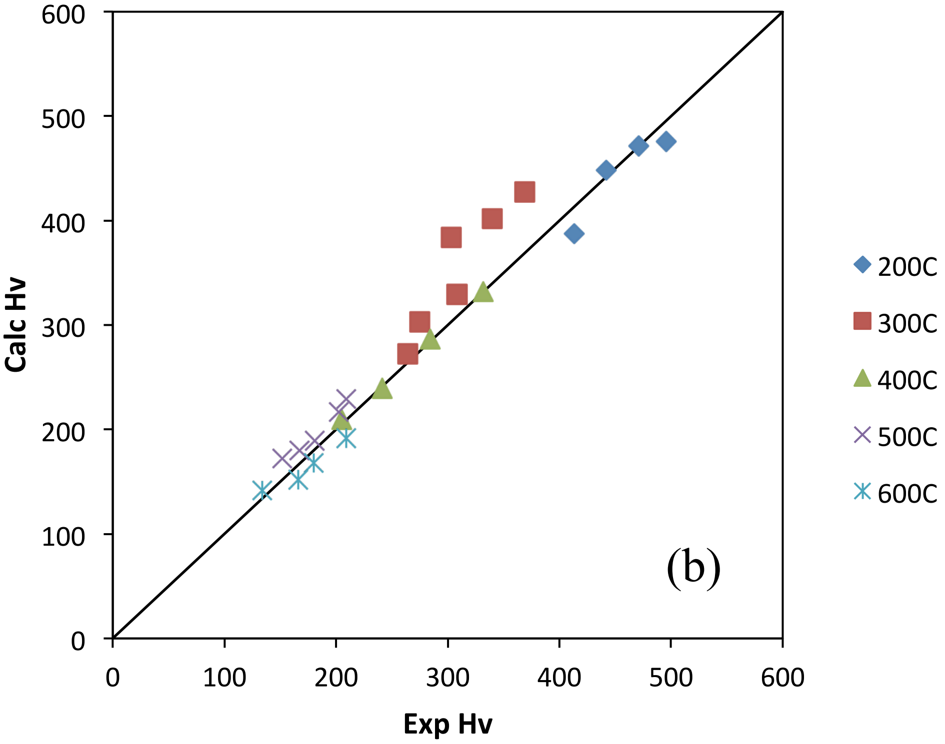


Figure 7. Comparison between calculated and experimentally observed [5] hardness after tempering for various times for (a) 0.097%C and (b) 0.18%C martensitic steels.

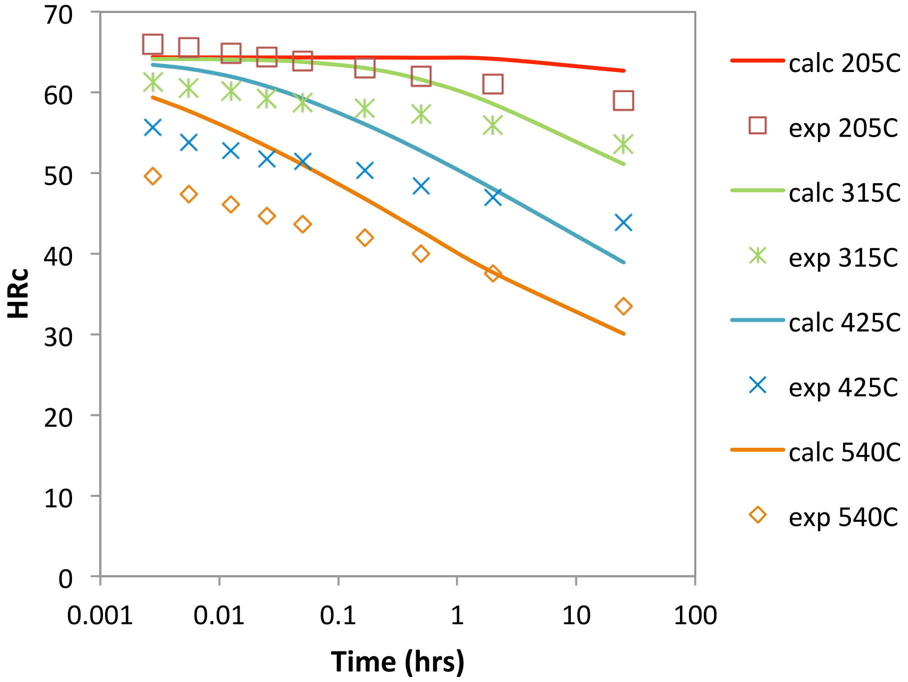


Figure 8. Plots of calculated and experimental [6] hardness vs time after tempering for a 0.82%C martensitic steel.