

# Time–temperature–precipitation diagrams of carbide evolution in low alloy steels

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## Abstract

Previously published time–temperature–precipitation diagrams showing carbide evolution were modified with the use of additional experimental data. The same low alloy steels as investigated originally were annealed at 793 and 873 K for 3000 and 10,000 h which, compared to the longest annealing time in the previous investigation of 1000 h, brings the system closer to equilibrium. Carbides extracted into carbon replicas were characterised by transmission electron microscopy, including electron diffraction and energy dispersive X-ray spectroscopy. The results of the additional experiment presented in the modified diagrams provide more information about the evolution and stability of  $M_3C$ ,  $M_2C$ ,  $M_7C_3$ ,  $M_{23}C_6$ ,  $M_6C$  and  $MC$  in the investigated steels.

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## 1. Introduction

Forty-five years ago, the concept of time–temperature–precipitation diagram (TTP) was used by Baker and Nutting [1] to describe the carbide evolution during tempering of the 2.25Cr–1Mo steel (Fig. 1). The experimental conditions, characterised by the time and temperature of tempering, were assigned to different regions according to the carbides identified. Subsequently, many studies related to the carbide structure, compositional and morphological changes, stability, etc. [2–20] were completed. In some of them, e.g. [15–20], the TTP concept was maintained.

Four low alloy steels (Table 1) were investigated in the work of Výrostková et al. [19]. As-quenched samples of the steels were annealed (tempered) at 773, 853, 933 and 993 K for various time up to 1000 h. Carbides of the type  $M_3C$ ,  $M_2C$ ,  $M_7C_3$ ,  $M_{23}C_6$ ,  $M_6C$  and  $MC$  were identified in the ferritic matrix using transmission electron microscopy (TEM). The results provided information on the various

carbide precipitations that supported the formulation of TTP diagrams for each of the steels (Fig. 2). These results may be summarised as follows:

- The *solid curves* separate:
  - (I) the  $M_3C$  region (below) from the  $M_3C + M_7C_3$  region (above);
  - (II) the  $M_3C + M_7C_3$  (below) and  $M_3C + M_2C + M_7C_3$  (above) regions;
  - (III) the  $M_3C + M_2C + M_7C_3$  (below) and  $M_2C + M_7C_3 + MC$  (above) regions;
  - (IV) the  $M_2C + M_7C_3 + MC$  (below) and  $M_7C_3 + MC$  (above) regions.
- The *dashed curve* characterises the *region of the  $M_{23}C_6$  existence*; the carbide exists in the region below the curve position.
- The *C-type dash-dot curve* characterises the *region of the  $M_6C$  existence*; the carbide exists in the closed region adjacent to the C-curve from the right.

For the interpretation of the diagrams illustrated in Fig. 2, overlapping has to be considered of all the regions present.

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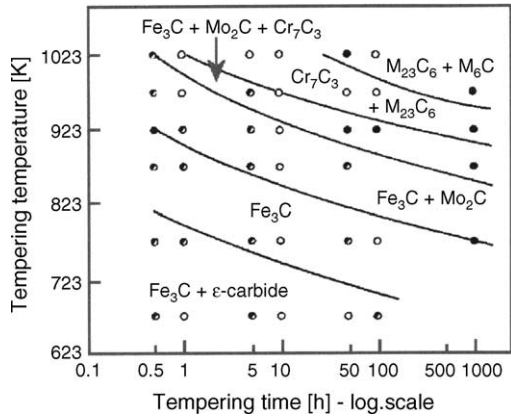


Fig. 1. Time–temperature–precipitation diagram showing evolution of carbides during tempering of the 2.25Cr–1Mo steel [1].

For instance, after annealing of steel 2 at 890 K for 4 h (the condition is marked with the solid octagon in Fig. 2), the carbides  $M_3C$ ,  $M_7C_3$  (both present in the relevant region) and  $M_{23}C_6$  (the octagon lies also inside the region for  $M_{23}C_6$ ) can be observed. Similarly, after annealing for 1000 h at 920 K (solid triangle) the carbides  $M_3C$ ,  $M_2C$ , MC (all present in the relevant region),  $M_{23}C_6$ , and  $M_6C$  can be observed.

The purpose of the present study was to improve the originally proposed time–temperature–precipitation diagrams [19] with the help of additional experimental data obtained for two further tempering temperatures and longer

Table 1

Chemical compositions of investigated steels; mass contents of elements are given in weight percent

Steel	C	Mn	Si	Cr	V	Mo	P	S	Fe
1	0.09	0.66	0.32	2.40	0.02	0.70	0.011	0.006	bal.
2	0.10	0.66	0.35	2.55	0.12	0.73	0.015	0.005	bal.
3	0.10	0.67	0.27	2.62	0.32	0.70	0.014	0.007	bal.
4	0.12	0.71	0.34	2.57	0.34	0.95	0.015	0.018	bal.

tempering times. We have studied the same steels and used the same experimental methods so as to ensure compatibility between the original and the new experiments.

## 2. Experimental

The steels (Table 1) were melted in a vacuum furnace, forged to rods, austenitised at 1523 K for 0.75 h and quenched into an aqueous solution of potassium hydroxide. The as-quenched samples were annealed at 793 and 873 K for 3000 and 10,000 h. Particles of secondary phases were extracted into carbon replicas and identified in a TEM Philips CM12 working at 120 kV. For characterisation of the particles, selected area electron diffraction (SAED) and energy dispersive X-ray spectroscopy (EDX) were used. Metal compositions of the analysed particles were determined from EDX spectra with software for thin samples. No corrections for absorption or fluorescence were

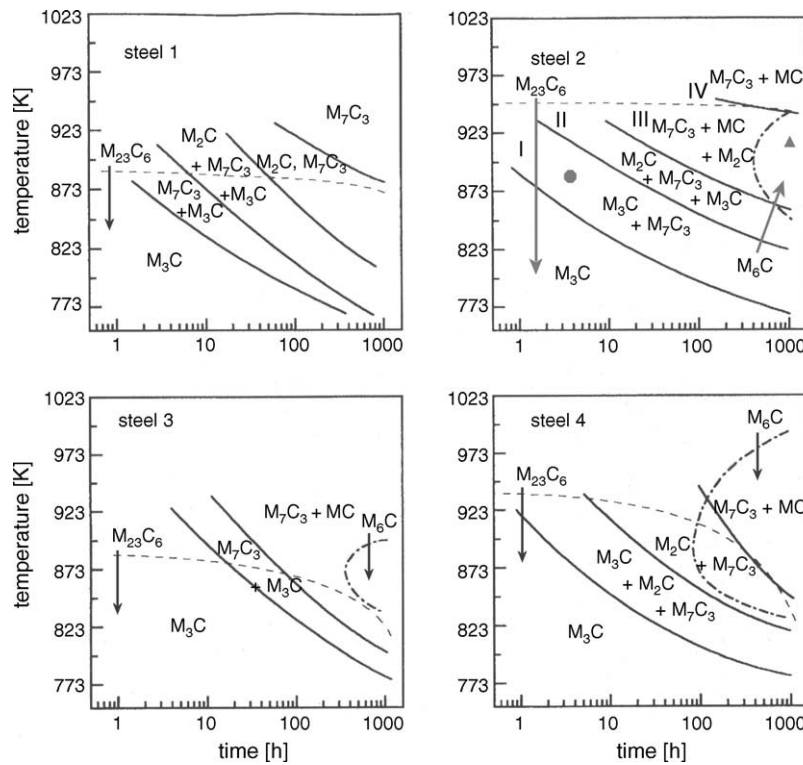


Fig. 2. Time–temperature–precipitation diagrams showing evolution of carbides during tempering (annealing) of low alloy steels [19]. Chemical compositions of the steels marked with numbers 1–4 are given in Table 1.

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