ARCHIVES of
Computational Materials Science and Surface Engineering

International Scientific Journal published quarterly by the Association of Computational Materials Science and Surface Engineering

2009 • Volume 1 • Issue 2 • 120-124

An analysis of modified Jominy-test (JMC®-test)

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Received in a revised form 16.02.2008; published 15.02.2009

ABSTRACT

Purpose: The performance and possibilities of application of modified Jominy-test (JMC®-test) in computer simulation of high-hardenability steel quenching were investigated. JMC®-specimen and cylindrical specimen has similar cooling curves if the cylindrical specimen has been quenched in oil or cooled in air.

Design/methodology/approach: The performances of investigated JMC®-test have been estimated by comparison of cooling curves of JMC®-specimen and cylindrical one cooled in different quenchants.

Findings: Based on the sufficiency of both, time of cooling and similarity of cooling curves of investigated workpieces and JMC®-specimen it can be concluded that JMC®-test can be accepted as very useful test for estimation of the hardness of quenched workpieces made of high-hardenability steels.

Research limitations/implications: The cooling curves of JMC®-specimen and the cooling curves of cylindrical specimens have been given by computer simulation and more experimental researches are advisable.

Practical implications: The simulation of quenching based on modified Jominy-test can be applied for steels with high hardenability. This method of simulation is especially suitable for tools and dies steels.

Originality/value: Using the results of simple modified Jominy-test (JMC®-test) in numerical modeling of steel quenching it is possible to simulate hardness in quenched specimen of high-hardenability steel.

Keywords: Quenching; Computer simulation; High-hardenability steels

Reference to this paper should be given in the following way:

B. Smoljan, D. Iljkić, S. Smokvina Hanza, F. Traven, An analysis of modified Jominy-test (JMC®-test), Archives of Computational Materials Science and Surface Engineering 1/2 (2009) 120-124.

METHODS OF ANALYSIS AND MODELLING

1. Introduction

Computer simulation of quenching includes several different analyses [3]. Research of numerical simulation of hardness and microstructure distribution in quenched steel specimen is one of the high priority researches in simulation of phenomenon of steel quenching. The investigation of steel quenching suggests that choosing a proper representative of the cooling phenomenon, which is relevant for structure transformation, is one of the most important factors for a good simulation of hardening.

One of the most common methods of computer prediction of quenching results is based on the chemical composition of steel and on the sample dimensions [1,2]. Moreover, prediction of microstructure composition usually is based on semiempirical methods derived from kinetic equations of microstructure transformation [6]. Then, the predicted microstructure composition can be used to predict mechanical properties, mostly focused on hardness.

Beside these methods, mathematical model of steel quenching can be based on calculated characteristic time of cooling [9,10]. Usually, relevant time for quenching results is the cooling time from 800 to 500 °C, $t_{8/5}$ [4,7]. To accept the assumption that the equal cooling time $t_{8/5}$ of several samples indicates their equal hardness, the history of cooling of these samples must be the same or similar, i.e. their cooling curves must be similar. By involving the cooling time $t_{8/5}$ in the mathematical model of steel hardening, the Jominy-test results could be involved in the model.

2. Simulation of hardness based on the cooling time $t_{8/5}$ using the JMC®-specimen

The structure transformations and hardness distribution can be estimated based on time, relevant for structure transformation. Usually, if the cooling time $t_{8/5}$ is equal in two different specimens, i.e. quenched workpiece and Jominy-specimen, the hardness of these two specimens are equal. In the developed computer simulation of hardenability of quenched workpiece, the hardness at different workpiece points is estimated by the conversion of the cooling time $t_{8/5}$ to the hardness. This conversion is provided by the relation between the cooling time $t_{8/5}$ and distance from the quenched end of the Jominy-specimen (Figure 1) [7,11]. The cooling time $t_{8/5}$ can be predicted by numerical modelling using the finite volume method [5].

For prediction of hardness of quenched workpiece, it is necessary that the cooling times $t_{8/5}$ for austenite decomposition in martensite, bainite, pearlite or ferrite of investigated workpiece and the cooling times $t_{8/5}$ of Jominy-specimen are in the same range. Because of high hardenability, the cooling times $t_{8/5}$ for austenite decomposition of most steels for tools and dies are not comparable with the cooling times $t_{8/5}$ of Jominy-specimen and there are limits in application of original Jominy-test in computer simulation of quenching of this kind of steels [12]. Figure 2 qualitatively represents austenite decomposition of some steels for tools and dies i.e. high-hardenability steels and it is visible that the cooling times $t_{8/5}$ of austenite decomposition are ranged from 200 to 1000 s. The cooling time $t_{8/5}$ for bainite transformation of steels X38CrMoV51 and X45NiCrMo4 is greater than 1400 s. The cooling time $t_{8/5}$ for pearlite transformation of steel X45NiCrMo4 is greater than 45000 s. For other steels start of bainite and pearlite transformation in TTT-diagram matches the cooling times $t_{8/5}$ in interval between 200 and 1000 s. Original Jominy-test gives the cooling times $t_{8/5}$ up to a maximum of 200 s (Figure 1), and it is obvious that original Jominy-test is not suitable for prediction of hardenability of steels for tools and dies.

To achieve times of cooling $t_{8/5}$ longer than 200 s, the modified Jominy-test was designed for high-hardenability steels, i.e. steels for tools and dies. The assembly of modified Jominy-test is shown in Figure 3. Instead of conical JM®-specimen [11], the cylindrical JMC®-specimen was used. JMC®-specimen in this case is end-quenched during the test. Other pieces of assembly are slowly cooled.

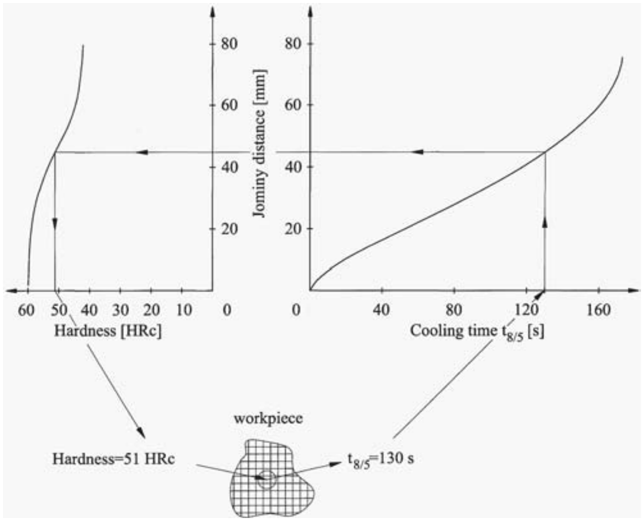

Fig. 1. Conversion of the cooling time $t_{8/5}$ to the hardness

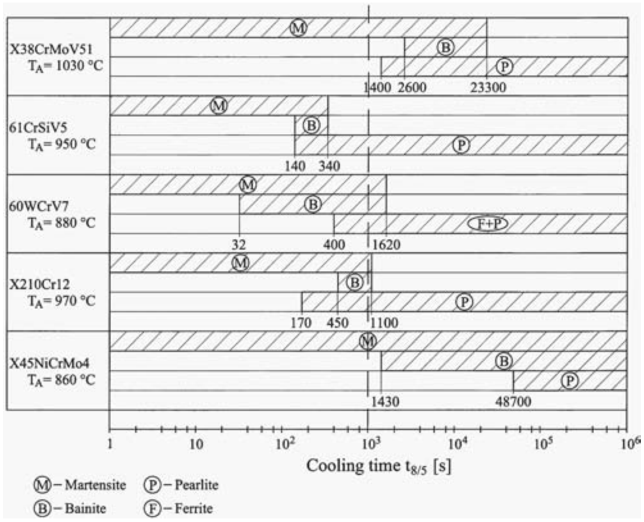

Fig. 2. Diagram of cooling times $t_{8/5}$ of several different steels for tools and dies

The JMC®-specimen can be used in computer simulation of quenching of high-hardenability steels, in similar manner as Jominy-specimen in computer simulation of quenching of low alloyed steels.

3. Comparison of cooling rates of cylindrical specimens and JMC®-specimen

If the hardness of quenched steel workpieces could be estimated using the equivalence of time of cooling $t_{8/5}$ in actual location of investigated workpiece and the JMC®-specimen

(Fig. 4), kinetics and history of microstructure transformation during the cooling have to be similar in the JMC®-specimen and actual steel workpieces for which the hardness have to be determined. So that it is necessary to compare the cooling curves of actual workpieces and the cooling curves of JMC®-specimen.

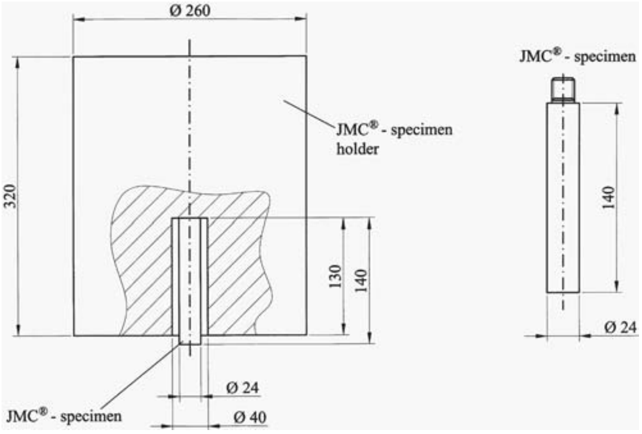

Fig. 3. JMC®-specimen and JMC®-specimen holder, all dimensions in mm

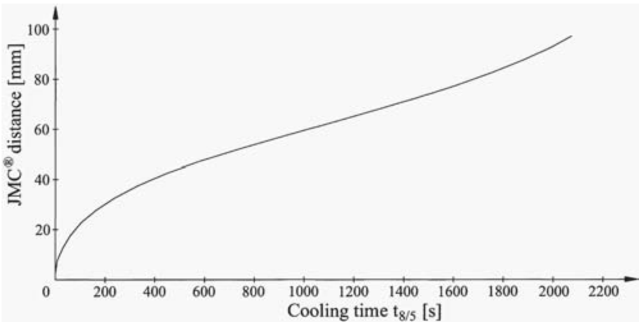

Fig. 4. Distance from the quenched end of JMC®-specimen vs. cooling time $t_{8/5}$

In order to compare the kinetics of the cooling in the JMC®-specimen and actual steel workpieces the cooling curves of steel workpieces has been compared to the cooling curves in different locations of JMC®-specimen. Cooling curves in points at the depth of 0.8 mm from the surface and at different distances from the quenched end of JMC®-specimen has been given by computer simulation. Computer simulation of cooling curves of cylindrical specimens (workpiecese), that heights are equal to four diameter (4D), has been done in different points of the cross section at their half of height. For comparison of cooling curves of cylindrical specimens and cooling curves of JMC®-specimen, the characteristic temperature of 500 °C has been specially emphasized. Since relevant time of cooling is the time of cooling between 800 and 500 °C, it is necessary to start with cooling times calculations in the moment when temperature is equal to 800 °C.

In Figures 5 and 6 the cooling curves of different cylindrical specimens quenched in oil are compared to the cooling curves in different locations of JMC®-specimen.

The cooling curves of cylindrical specimens quenched in oil and the cooling curves in different locations of JMC®-specimen are similar enough to encourage the usage of the JMC®-specimen in the estimation of hardness of quenched steel specimens.

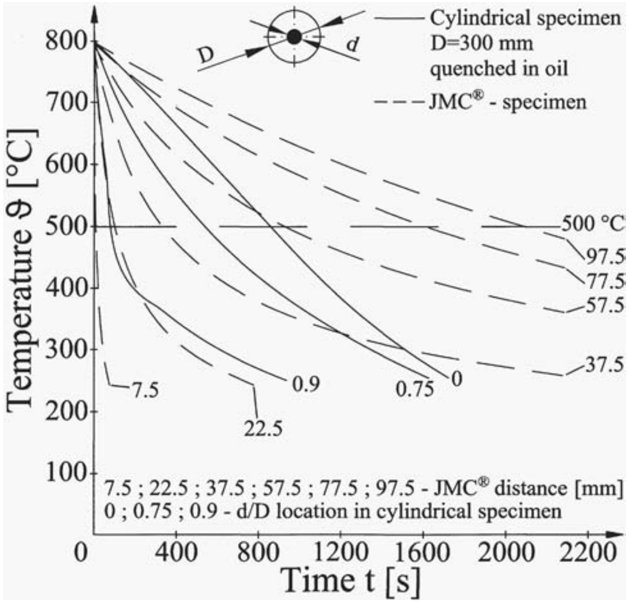

Fig. 5. Cooling curves of cylindrical specimen (D=300 mm)

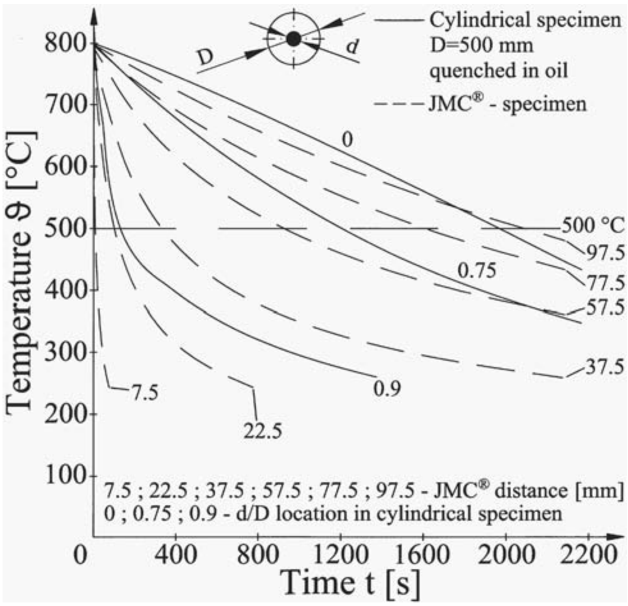

Fig. 6. Cooling curves of cylindrical specimen (D=500 mm)

Satisfying results of mechanical properties of cylindrical specimens of high-hardenability steels, with small dimensions can be obtained by cooling in air. The cooling curves of cylindrical specimen cooled in air and the cooling curves in different locations of the JMC®-specimen are shown in Figures 7-10.

The cooling curves of cylindrical specimens are even more similar to the cooling curves of the JMC®-specimen if they are cooled in air than in oil.

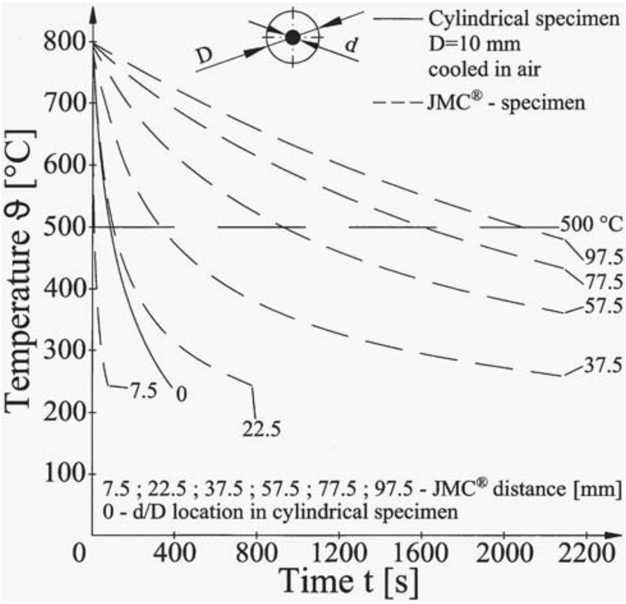

Fig. 7. Cooling curves of cylindrical specimen (D=10 mm)

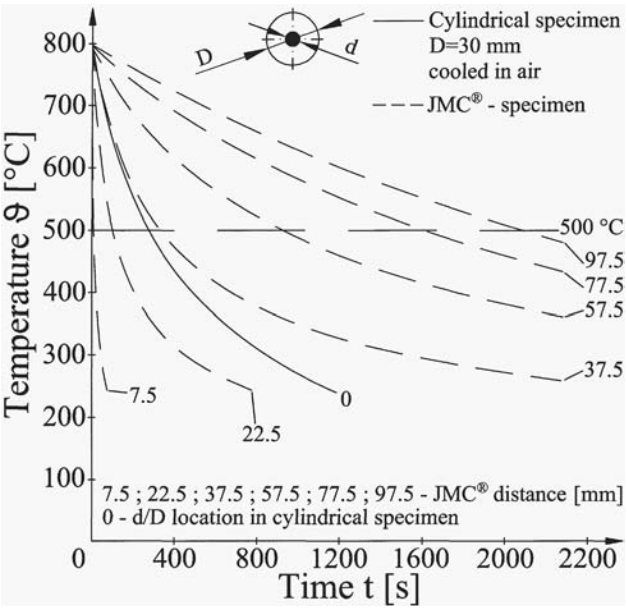

Fig. 8. Cooling curves of cylindrical specimen (D=30 mm)

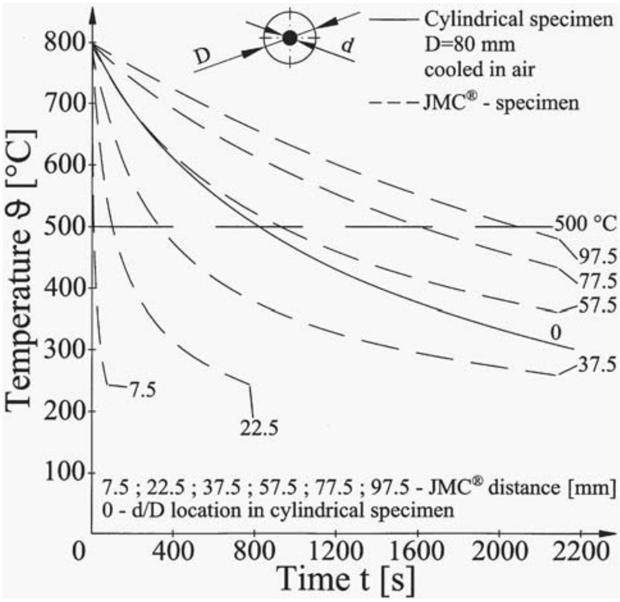

Fig. 9. Cooling curves of cylindrical specimen (D=80 mm)

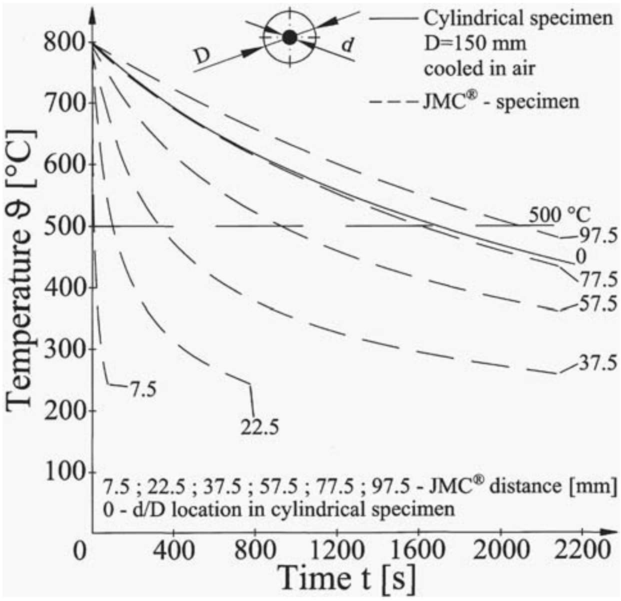

Fig. 10. Cooling curves of cylindrical specimen (D=150 mm)

4. Conclusions

By comparing times of cooling of the JMC®-specimen and the times of cooling required to achieve martensite microstructure in quenching of high-hardenability steels i.e. steels for tools and dies it is visible that the JMC®-specimen is adequate for estimation of hardness of quenched workpieces made of high-hardenability steels.

Cooling curves of cylindrical specimen quenched in oil and cooling curves of JMC®-specimen are similar, while cooling curves of cylindrical specimen cooled in air and cooling curves of JMC®-specimen are even more similar.

Based on the adequacy of reached time of cooling and similarity of cooling curves in investigated workpieces and JMC®-specimen it can be concluded that JMC®-test can be accepted as very useful test for estimation of the hardness of quenched workpieces made of high-hardenability steels.

The final evaluation of the applicability of the JMC®-test in simulation of quenching of steels can be obtained using the further experimental research.

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