



# Optimizing hardenability of high chromium white cast iron

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**Abstract:** The formulas proposed by J. Dodd and J. L. Parks for calculating the hardenability of high-Cr white cast iron under continuous cooling condition was recommended. For broader application, some supplements were made to the formula. Through tests on the half-cooling time of typical castings, the compositions of ideal alloys were precisely designed using the Dodd's formula. Hardness testing of heat-treated castings showed that the designed compositions were correct. The application of castings demonstrated excellent abrasion resistance.

**Key word:** high-Cr white cast iron; half-cooling temperature; half-cooling time; continuous cooling transformation diagram

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High Cr white cast irons possess a combination of excellent abrasion resistance and a reasonable degree of toughness. The microstructure of high-Cr white cast irons consists of a composite of large primary and/or eutectic carbides in type  $M_7C_3$  (where  $M=Cr, Fe, Mo, Mn, etc.$ ) and a softer matrix. The matrix structure favored in the as-cast irons is predominantly austenite which can be changed to predominantly martensite after air quenching.

At present, when factories produce high-Cr white cast iron, they choose the chemical composition of the cast iron mainly by experience. For example, in the production of heavy sectioned castings, more alloying elements are added, such as Cu, Ni and Mo to ensure a good hardenability as the castings are air-cooled. Strictly control of alloying element is essential in the production of high-Cr white cast irons. Many of the complaints of poor abrasion resistance can be traced back to scanty alloy element contents which result in an iron with abnormally low hardenability. But, excessive alloying element content will increase the production cost.

Therefore, accurate design of chemical composition of the iron casting according to the casting thickness of section becomes an important topic in producing high-Cr white cast irons. In the present study, this issue on alloying element content is discussed.

## 1 The formulas of hardenability of continuous cooling transformation of high-Cr white cast iron

J. Dodd and J. L. Parks studied the effects of alloying additions on the CCT kinetics and introduced two formulas to calculate the pearlite starting time  $t$ (s) according to experimental data in reference [1]:

$$lgt = 2.24 + 0.58Mn + 0.41Mo + 0.84Ni + 0.46Cu \quad (1)$$

The validity scope of this formula was 2.88%-2.96% C, 16.9%-

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17.6% Cr, 0.52%-0.61% Si, 0.75%-3.08%Mn, 0.04%-2.89%Mo, 0.00%-2.09% Ni, 0.00%-1.95% Cu.

$$lgt = 2.90 - 0.51C + 0.05Cr + 0.38Mo \quad (2)$$

The validity scope of formula (2) was 1.95%-4.31% C, 10.80%-25.80% Cr, 0.02%-3.80% Mo.

By using the coefficient of Cr in formula (2), when the Cr content is larger than 17.6% in the high-Cr white cast irons, following formula can be adopted to calculate the time  $t$ :

$$lgt = 2.24 + 0.58Mn + 0.41Mo + 0.05(Cr - 17.6) + 0.84Ni + 0.46Cu \quad (1')$$

Figure 1 is the continuous cooling transformation diagram of 20Cr-2Mo-1Cu iron. According to the data of Fig.1, the time  $t$  can be calculated by formula (1')

$$\begin{aligned} lgt &= 2.24 + 0.58 \times 0.73 + 0.41 \times 2.08 + 0.05 \times (19.35 - 17.6) + \\ &\quad 0.46 \times 1.02 \\ &= 4.0729 \\ t &= 11828 \text{ (s)} \end{aligned}$$

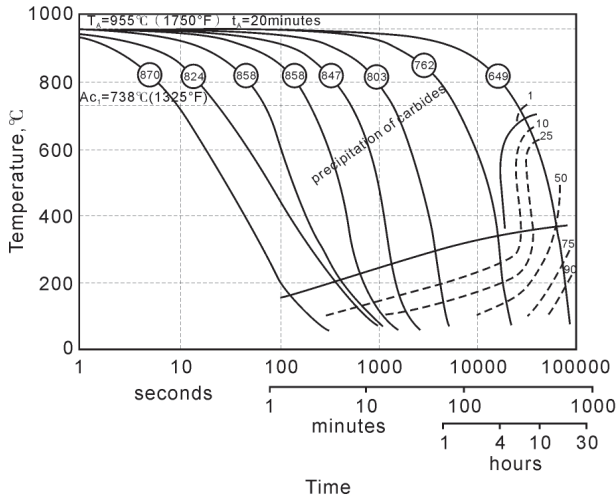
It can be seen from Fig. 1 that the  $t$  should be approximately 11400 s, which is similar to the calculated value.

## 2 Half cooling time and half cooling temperature

In order to study the microstructure of continuously cooled high-Cr white cast irons, the researchers have put forward the concept of the half-cooling time and half-cooling temperature.

W. Fairhurst and K. Röhrig<sup>[2]</sup> defined the half-cooling time as the time taken to cool through half the temperature difference between the quenching temperature and ambient. With a quenching temperature of 1000 °C, for example, this would be the time required to change/decrease about 490 °C.

W. W. Cias<sup>[3]</sup> defined the half-cooling time as the time required to cool from the austenitizing temperature ( $T_A=955$  °C) to the temperature  $T_{HC}$  that is midway between  $T_A$  and room



Note: The composition was 2.89% C, 19.35% Cr, 2.08% Mo, 1.02% Cu, 0.73%Mn, and 0.55% Si. The samples were held at 955°C for four hours in a furnace, and then transferred to a dilatometer. When reheated to 955°C and held for 20 min, soak cooled at the indicated rates. The numbers in circles give the Vickers-hardness.

Fig. 1 Continuous cooling transformation diagram for 20-2-1 LC iron.

temperature (25 °C):  $T_{HC} = (T_A - 25) / 2 + 25 = (T_A + 25) / 2 = (955 + 25) / 2 = 490$  °C.

Figure 2 shows the continuous cooling transformation diagram for the white cast iron containing 2.93% C, 0.60% Si, 0.78% Mn, 17.4% Cr, and 0.04% Mo, which was austenitized at 955°C for 20 minutes. In this case,  $T_A = 955$  °C, and the half-cooling temperature was 490°C.

The bainite start half-cooling time determines the extent of the exclusive martensitic transformation time range. The pearlite start half-cooling time determines the time spectrum of the exclusive occurrence of the martensitic and martensitically induced (bainitic) transformations. The two terms have also been defined diagrammatically in Fig. 2. This figure gives the temperature lines of Ms and the numbers in circles indicate the Vickers-hardness (HV).

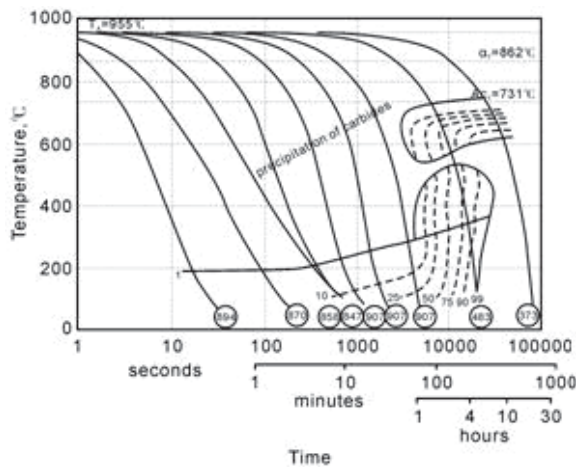


Fig. 2 Continuous cooling transformation diagram for the white cast iron containing 2.93% C, 0.60% Si, 0.78% Mn, 17.4% Cr, and 0.04% Mo, austenitized at 955°C for 20 min.

From Fig.2 it can be seen that the  $t$  and half-cooling time values determined by equation (1) and (1') were not close. When the  $t$  was greater than half-cooling time, the castings can be guaranteed to produce no pearlite and obtain martensite and retained austenite.

For the chemical content given in Fig. 2, the  $t$  is:

$$lgt = 2.24 + 0.58 \times 0.78 + 0.41 \times 0.04 = 2.706, t = 508 \text{ s.}$$

In Fig. 2 the left end of curve C was 400 s.

### 3 Effect of Si and C content

In high-Cr white cast iron when the Si content is higher than 0.6%, formula (1) can not be used to calculate the  $t$ . The silicon element decreases the hardenability of the high-Cr white cast iron. The contents of alloying elements given in Figs. 3 and 4 were the same except for Si (the content of Si was 0.93% in Fig. 4). From Figs. 3 and 4 the pearlitic starting time  $t$  can be determined respectively at 6 000 s and 4 500 s, a difference of 25 minutes between the two.

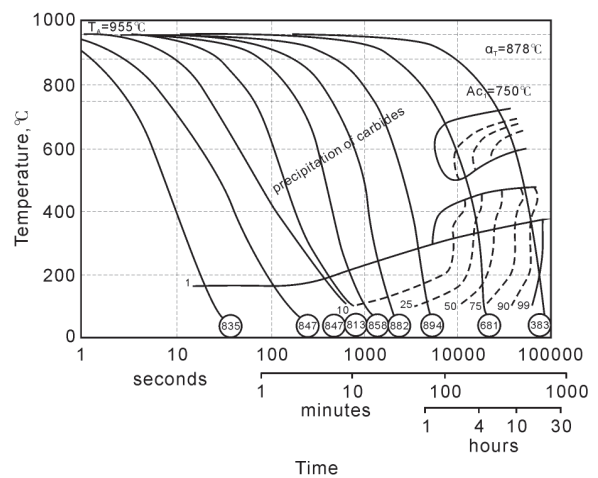


Fig. 3 Continuous cooling transformation diagram for the white cast iron containing 2.96% C, 0.52% Si, 0.79% Mn, 17.5% Cr, 0.98% Cu, and 1.55% Mo, austenitized at 955°C for 20 min.

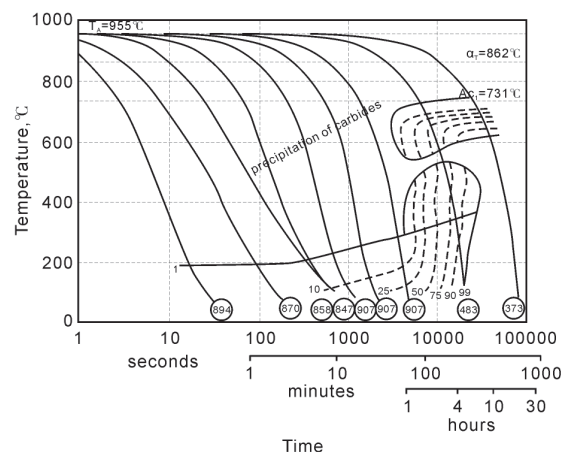
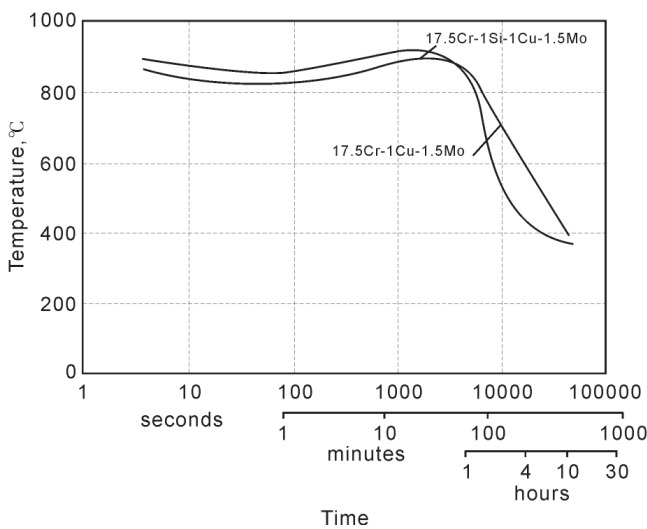


Fig.4 Continuous cooling transformation diagram for the white cast iron containing 2.96% C, 0.93% Si, 0.79% Mn, 17.5% Cr, 0.98% Cu, and 1.55% Mo, austenitized at 955°C for 20 min.

Figure 5 is the hardenability diagram on different silicon contents in cast iron. If the hardness of the sample reaches 750 HV (i.e. 61 HRC), the quenching process is successful and pearlite will not appear in the microstructure of the casting sample. If a horizontal line is drawn from 750 HV at the longitudinal coordinate in Fig. 5, the line will intersect with the hardenability curves of two alloys. Obviously, the horizontal line intersects the hardenability curve of the alloy with 1%Si first, then that with less silicon, suggesting that the quenching half-cooling time is shorter for the alloy with lower silicon content. In the area of half cooling time that represents successful quenching, the casting sample hardness was also higher.



The Si level used in Fig. 3 was lower than that in Fig.4, and the corresponding Ms temperatures were 180°C (Fig. 3) and 200°C (Fig. 4), respectively. So the high silicon content at 0.93% resulted in the reduction of the retained austenite and higher hardness.

The C content also affects the hardenability of high-Cr white cast iron. When the C content was higher than 2.96%, formula (1) can not be used to calculate the *t*. In this study, the coefficient of C in formula (2) on the high-Cr white cast irons was used to calculate the time *t*. Therefore, according to the following formula, the *t* can be calculated.

$$\lg |t| = 2.24 - 0.51(C - 2.96) + 0.05(Cr - 17.6) + 0.58Mn + 0.41Mo + 0.84Ni + 0.46Cu \quad (1'')$$

Figure 6 was the continuous cooling transformation diagram for a 15Cr-2Mo-1Cu white iron alloy. Using formula (1'') the time *t* can be calculated as follows:

$$\begin{aligned} \lg t &= 2.24 + 0.58 \times 0.72 - 0.51 \times (3.32 - 2.96) + 0.05 \times \\ &\quad (14.63 - 17.6) + 0.41 \times 2.05 + 0.48 \times 1.02 = 3.6564 \\ t &= 4533 \text{ s} \end{aligned}$$

The *t* was determined at about 4 300 s in Fig. 6, which was similar to the calculated value. However, the calculated value from formula (1) was *t*=9 760 s, demonstrating a very large error on the estimated half-cooling time.

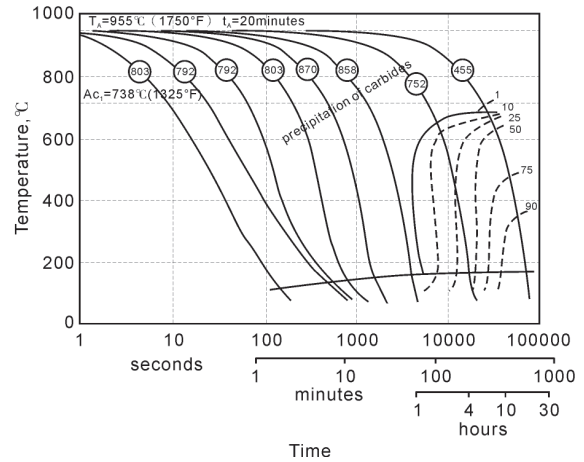


Fig.6 Continuous cooling transformation diagram for 15-2-1 LC iron.

The composition was 3.32% C, 14.63% Cr, 2.05% Mo, 1.02% Cu, 0.72%Mn, and 0.58% Si. The samples were held at 955°C for four hours in a furnace, and then transferred to a dilatometer. When reheated to 955°C and held for 20 min, soak cooled at the indicated rates. The numbers in circles give the Vickers-hardness.

### 4 Influence of the Cr/ C ratio and the Mo-content on half-cooling time

Figure 7 illustrates the effect of the Cr/C ratio on the maximum half-cooling time which avoids the formation of pearlite<sup>[2]</sup>. When using Fig.7, the half-cooling time must be calculated by the defining of W. Fairhurst. In order to extend the application range, the concept of Mo equivalent has been introduced in the present study based on the coefficients of alloy elements in Dodd's formula (1). This would determine the Mo equivalent of alloy element Ni at 0.84/0.41=2, and the Mo equivalent for Cu at 0.48/0.41=1.17. When the Mn content is less than 1.0%, this diagram can be used directly.

Figure 7 has also placed half-cooling times for three high-Cr-Mo white cast irons containing Cu (see the three black data points).

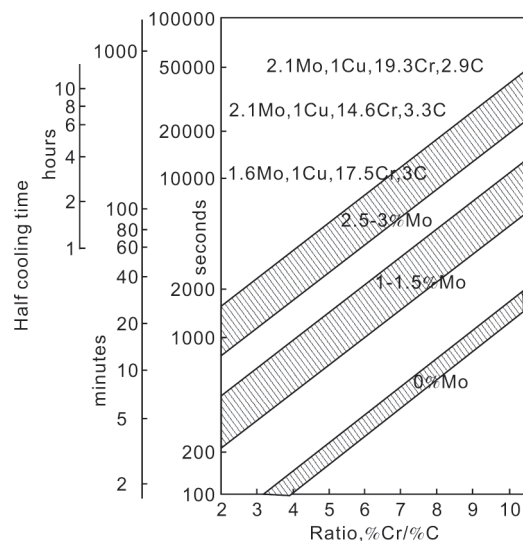


Fig. 7 Influence of the Cr/C ratio and the Mo content of hypo-eutectic high-Cr iron on the half-cooling time

## 5 Measurement of casting half-cooling time

Figure 8 is the schematic of a 330kg abrasion resistant platehammer. The required hardness for this test casting was greater than 60 HRC. In order to measure the casting half-cooling time, an aperture with a diameter of 15 mm and a depth of 65 mm was made in the center of the plate-hammer. The castings were austenitized at 1 000°C for four hours. According to the W. Fairhurst's method, the calculated half-cooling time was 490°C.

After soaked at 1 000 °C for four hours, the plate-hammer casting was taken out of the furnace and the cooling time started counting. In this case, a thermocouple was inserted in the center of the test casting to record the temperature. The time for the casting to cool down to 490 °C was 565 s.

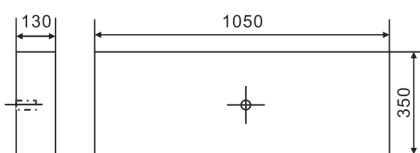


Fig. 8 Schematic drawing of impact plate-hammer

## 6 Confirmation of plate-hammer composition

It is common in practice that the Cr/C ratio is around 7 for high-Cr-Mo type of white iron alloys, and the related alloy elements are in the range of the 2.9%-3.2%C, 20%-23% Cr,

and 0.7%-1.0% Si. As the Si level higher than 0.6% made the hardenability of alloy to be decreased, the time  $t$  takes 120 min (30 min. more than the half cooling time of plate-hammer). Since Mo is appreciated in value rapidly, the lowest possible Mo content would be applied. The  $t$  is calculated according to the following data: 3.2% C, 21% Cr, 1% Mn, 0.4% Mo, 0.5% Ni, 1.0% Cu,

$$\begin{aligned} lgt &= 2.24 + 0.58 \times 1 - (3.2 - 2.96) \times 0.51 + 0.05 \times (21 - 17.6) \\ &\quad + 0.41 \times 0.4 + 0.84 \times 0.5 + 0.46 \times 1 = 3.9116 \\ t &= 8\ 158\ s = 136\ \text{min} > 120\ \text{min} \end{aligned}$$

The alloy contents used in the production were 2.9%-3.2% C, 20%-23% Cr, 0.7%-1.0% Si, 0.4%-0.5% Ni, 1.0%-1.2% Mn, 1.0%-1.2% Cu. The heat treatment was at 1 020 °C for 4-5 hours, followed by air cooling.

Actually, the measured hardness on plate-hammer castings was 62-63 HRC. The usage of these castings in service indicated that the high-Cr white cast iron has good abrasion resistance.

## References

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