Effect of Chromium on Microstructure and Properties of High Boron White Cast Iron

ZHONGLI LIU, XIANG CHEN, YANXIANG LI, and KAIHUA HU

In this article, the effect of chromium on microstructure and properties of high boron white cast iron was studied. The results indicate that the microstructure of high boron white cast iron with different chromium content comprises a dendritic matrix and interdendritic eutectics, and the eutectic compound has a M_2B-type chemical formula that does not change with the difference of chromium content. The increase of chromium not only increases the microhardness of boride, but also improves the morphology of boride, which is changed from continuous network to less continuous distribution. Moreover, with the chromium increase, martensite appears in the matrix under the as-cast condition, the appearance of which depends on the increase of chromium in the matrix and the uneven distribution of carbon in the matrix caused by chromium addition. After quenching in air, the matrixes of alloys all change to martensite. However, some secondary particles are found in the central area of the dendrite grains of alloys with higher chromium, and their existence is due to the difference of boron solubility in the matrix with different chromium content. In addition, the hardenability, hardness, and impact toughness are all improved with the increase in chromium.

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I. INTRODUCTION

HIGH boron white cast iron is a new kind of wear-resistant material, which takes borides as the strengthening phase and is different from conventional white cast irons with carbides as the strengthening phase. As borides have higher hardness and better thermal stability than carbides, they are more suitable to act as the strengthening phase.[1] This kind of material began to draw people's attention at the end of the 1980s and has been developed in several countries since then.[2–6] The marked advantage of high boron white cast iron is that the matrix and boride could be controlled, respectively, by carbon and boron content and, as a result, the strengthening and toughening matrix and adequate volume percentage of boride could be obtained at the same time, which is a great improvement and can make it possible to design the microstructure that we need. On the contrary, for conventional white cast iron with carbide, carbon affects not only the matrix but also carbide, which means the increase of matrix toughness is always at the cost of the decrease of carbide volume percentage, and *vice versa*. Therefore, it is difficult to balance the matrix and carbide in conventional white cast irons, and improving the toughness of conventional white cast iron is a continual topic of concern.

As we know, high chromium white cast iron has a better combination of hardness and toughness than plain and Ni-hard white cast iron, basically because the high chromium addition improves the carbide morphology and increases the carbide microhardness.[7,8] In this article, high boron white cast irons with different chromium content were developed to study the effect of chromium on their microstructure and properties.

II. EXPERIMENTAL PROCEDURE

The chemical compositions of the tested alloys are presented in Table I.

High boron white cast iron was melted in a 100-kg capacity medium-frequency coreless induction furnace with SiO_2 lining, with charge materials of steel scrap, graphite, Fe-B, Fe-Mn, Fe-Cr, and Fe-Si master alloys. Because boron is an active element, oxygen and nitrogen in the melt should be removed effectively to ensure the yield of boron, and so Al wire and Fe-Ti were added to remove oxygen and fix nitrogen before the Fe-B master alloy was added in. The melt was superheated to 1823 K, and then poured directly into a sand mold of Y blocks.

The test specimens were cut from the lower part of the Y blocks. The surface of specimens should be removed 3 mm to eliminate any oxidized layer to measure the as-cast hardness. The heat treatment of specimens was carried out in an electrical resistance furnace. Specimens were held at 1273 K for 2 hours, quenched in air, and then tempered at 473 K for 1 hour. After heat treatment, the impact test specimens were machined to 20 × 20 × 110 mm. Impact tests were completed using a 150-J capacity impact testing machine at room temperature. The impact toughness values reported in this

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Table I. Chemical Compositions of the Alloys (Weight Percent)

Alloy	B	C	Si	Mn	Cr	Ti	Al	S	P
A	1.44	0.28	0.62	1.01	4.12	0.015	0.021	0.0020	0.0022
B	1.44	0.29	0.58	0.98	6.34	0.019	0.025	0.0018	0.0021
C	1.44	0.28	0.63	1.06	9.25	0.013	0.020	0.0021	0.0022

article are averages of three tests. The hardness was tested on a Rockwell hardness machine. Five readings were taken on each sample and the average of them is reported here. The microhardness was tested on an NMt-3 machine, and the average of five readings is reported. The hardenability of specimens was tested according to the Jominy method, and the austenizing temperature and holding time were 1273 K and 30 minutes, respectively. The microstructure of the specimens was examined with a Neophot 32 optical microscope (OM, Carl Zeiss Co., Germany) and a FEI Quanta 200 FEG scanning electron microscope (SEM, FEI Co., Holland) with energy-dispersive analysis by X-ray (EDAX) after etching with 4 pct nital solution. X-ray diffraction (XRD) analysis was performed on a D/max-RB X-ray diffractometer (Rigaku Industrial Corporation, Japan). The specimens were scanned using Cu K_α radiation at 40 kV and 300 mA, and the scanning speed (2θ) was 6 deg min^{-1}.

III. RESULTS AND DISCUSSION

A. *As-Cast Microstructures of the Alloys*

The as-cast microstructures of alloys A, B, and C are shown in Figure 1. In the condition of as cast, the

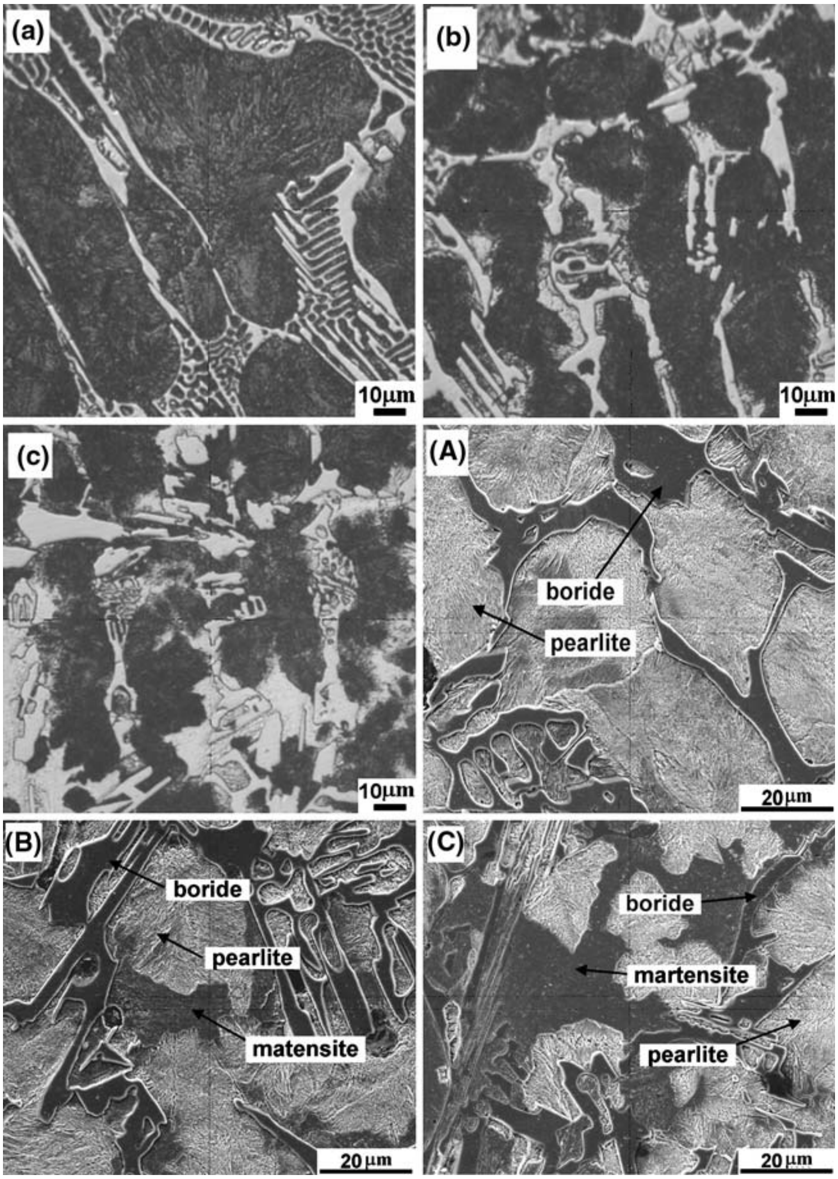

Fig. 1—As-cast microstructure of the alloys: (*a*) OM micrography of alloy A, (*b*) OM micrography of alloy B, (*c*) OM micrography of alloy C, (*A*) SEM micrography of alloy A, (*B*) SEM micrography of alloy B, and (*C*) SEM micrography of alloy C.

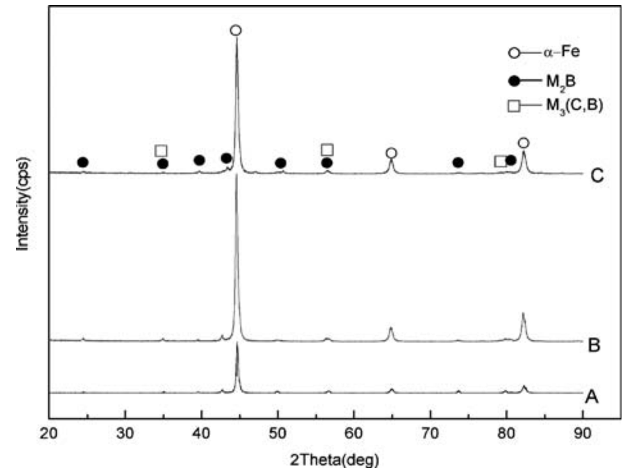

Fig. 2—XRD patterns of alloys A, B, and C under the as-cast condition.

microstructures of these three alloys all comprise a dendritic matrix and interdendritic eutectics, which would be analyzed, respectively.

1. *Eutectic compound*

For wear-resistant white cast irons, the eutectic compounds play a great role in the microstructure. As these eutectic compounds are usually hard and brittle, their distributions and morphology in microstructure are the most concerned problems. The eutectic compound in these three alloys has the chemical formula of M_2B (Figure 2), which does not change with the chromium content. Here M represents Fe, Cr, or Mn identified from the EDAX spectra of boride in alloys A, B, and C (Figure 3).

According to the EDAX spectra of boride in alloys A, B, and C, it can be seen that the content of chromium in boride is different, which is the highest in alloy C, followed by alloy B, and the least in alloy A (Figure 3). The difference of chromium content of boride in alloys A, B, and C results in the change of boride microhardness. Table II shows the microhardness of different phases in alloys. The boride microhardness increases with the increase in chromium contents. In other words, the higher chromium leads to the higher content of chromium in boride, and the higher chromium content in boride leads to the higher microhardness of boride.

Moreover, the change of chromium content in alloys affects not only the microhardness of boride but also the morphology of boride. The microstructure of the alloys in Figure 1 indicates that the morphology of alloy A with lower chromium is continuous and fishbone like. With the increase in chromium, the morphology of boride becomes less continuous and platelike in alloys B and C, which is close to the morphology of carbide in high chromium white cast iron. Therefore, the higher chromium content is beneficial to the improvement of boride.

2. *Matrix*

The matrixes of the three alloys also differ from each other besides the boride. For alloy A with lower chromium content, the matrix only contains pearlite (Figures 1(a) and (A)), but for alloys B and C with more chromium, another phase appears. This phase, which is light under OM and dark under SEM (Figures 1(b), (B), (c), and (C)), is different from pearlite and difficult to etch with nital solution, and the volume percentage of this phase increases with the increase of chromium. When etched with another agent for alloy C, which

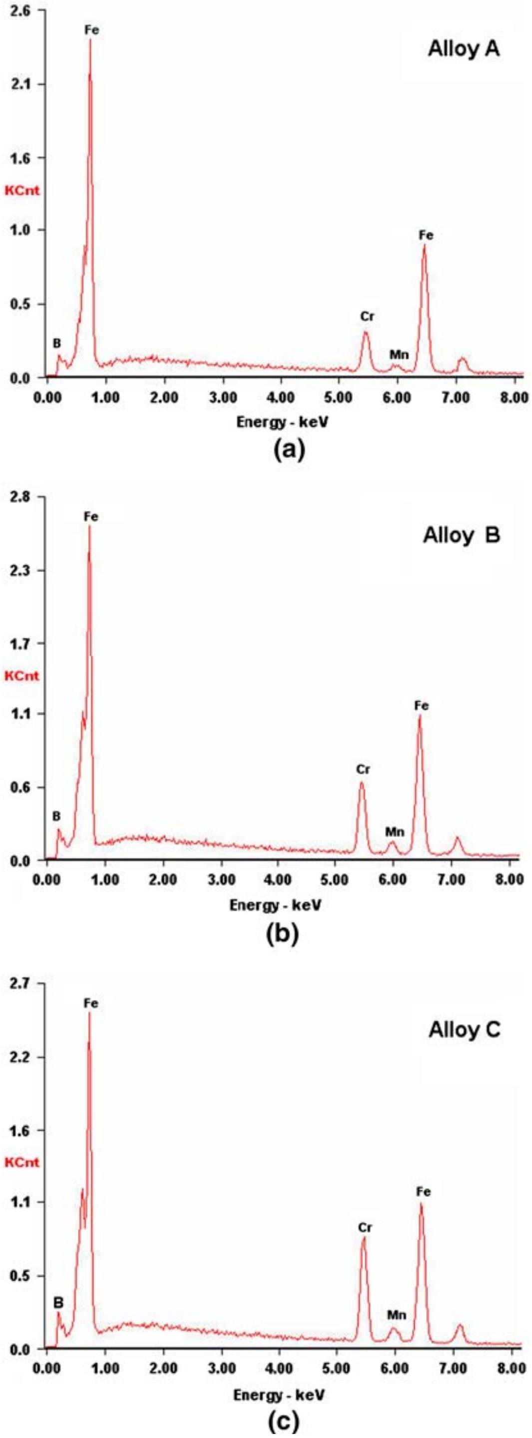

Fig. 3—EDAX spectra of boride in alloys A, B, and C.

Table II. Microhardness of Different Phases of the Alloys under As-Cast Condition

Sample	Boride (HV)	Pearlite (HV)	New Phase (HV)
A	1604.2	228.1	—
B	1810.7	256.4	435.7
C	2011.4	282.3	455.6

contains 10 vol pct HNO_3, 3 vol pct HCl, 10 vol pct saturated $FeCl_3$, and 77 vol pct ethanol, this phase looks like low-carbon martensite (Figure 4); moreover, it has a high microhardness (Table II), so this phase should be martensite, and the reason for its appearance will be discussed subsequently.

In addition, the microhardness of pearlite in alloys A, B, and C is also increased with the increase of chromium. To sum up the effect of chromium on the matrix, the higher chromium not only leads to the appearance of martensite, but also affects its volume percentage; at the same time, the microhardness of pearlite also increases.

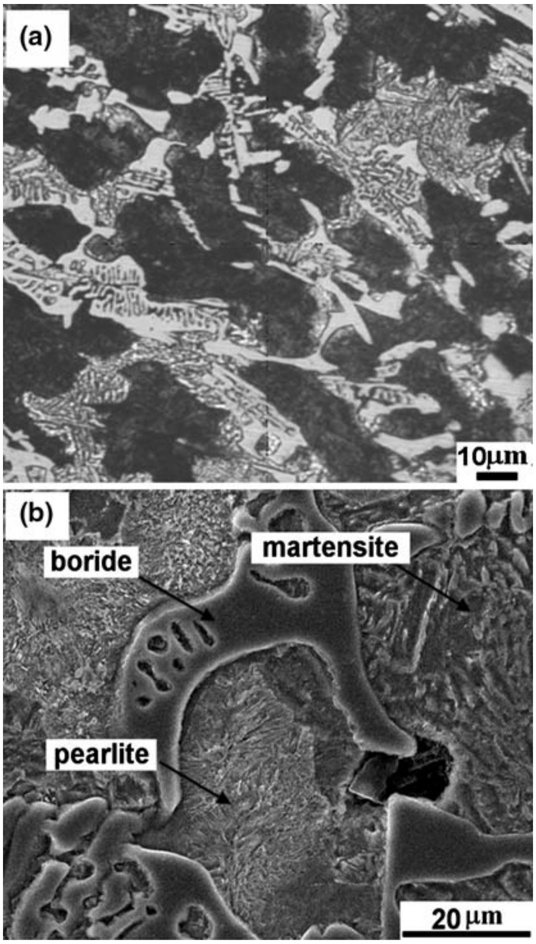

Fig. 4—As-cast microstructure of alloy C: (*a*) OM micrography of alloy C and (*b*) SEM micrography of alloy C.

Table III. Matrix Compositions of Alloys A, B, and C Detected by EDAX

Element Content (Wt Pct)	A	B		C	
	Pearlite	Pearlite	Martensite	Pearlite	Martensite
C	0.33	0.35	0.17	0.42	0.17
Cr	3.81	6.06	4.23	8.75	6.52
Si	0.97	1.04	1.08	0.89	1.01
Mn	1.31	1.55	1.25	1.26	1.40

In order to understand the changes of matrix caused by chromium, the compositions of different regions in the matrix of alloys A, B, and C were tested with EDAX, and the results are listed in Table III.

The increase of Cr leads to the appearance of martensite in alloys B and C; the basic reason is that the Cr content in the matrix increases (Table III) and improves the hardenability of the matrix. Another phenomenon that the carbon is distributed unevenly in martensite and pearlite of alloys B and C cannot be neglected (Table III). The martensite contains low carbon content, but pearlite contains high carbon content. It has been found that boron can increase the hardenability of steel greatly with just a little content, but more boron would damage this effect; at the same time, low carbon content is favored.[9–11] The higher Cr in alloys B and C leads to the uneven distribution of carbon in the matrix; the low-carbon region has better hardenability than the high-carbon region, and therefore, the former changes to martensite.

B. *Microstructure after Heat Treatment*

After heat treatment, the matrix of alloys A, B, and C changes to martensite, and the morphology of boride is almost unchanged (Figure 5). However, some particles about 1 μm in size appear in the central region of the dendritic matrix grains in alloys B and C. These particles were considered $M_{23}(B,C)_6$, where M represents Fe, Cr, or Mn.[4] Why do high boron white cast irons with higher chromium precipitate $M_{23}(B,C)_6$ particles? Guo[12] has demonstrated that the diameter of the Cr element is larger than that of Fe; hence, it would enlarge the crystal lattice parameter when Cr is dissolved in Fe by means of substitution. Therefore, with more chromium addition, the matrix would dissolve more boron and result in the $M_{23}(B,C)_6$ precipitation.

IV. EFFECT OF CHROMIUM ON THE PROPERTIES OF THE ALLOYS

A. *Effect of Chromium on Hardenability*

The effect of chromium on hardenability is shown in Figure 6. The results indicate that the hardenability of high boron white cast iron increases with the chromium increase.

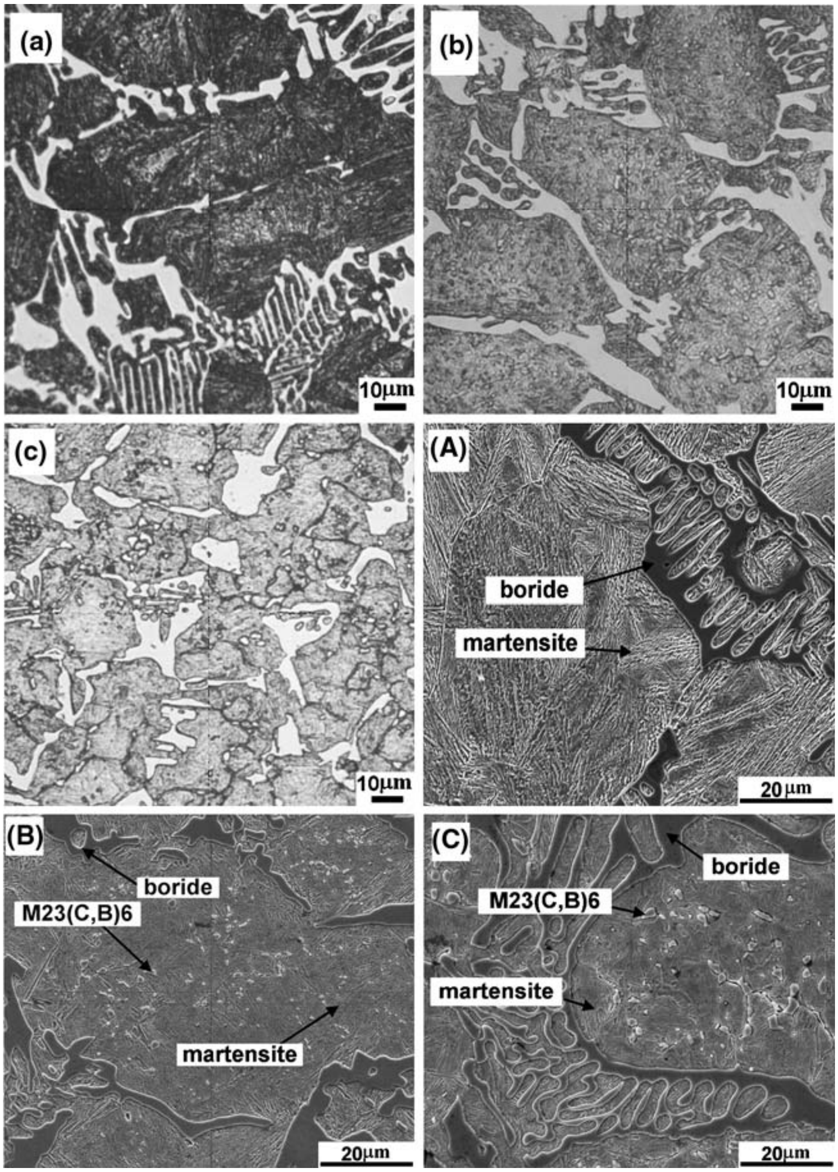

Fig. 5—Microstructure of the alloys after heat treatment: (*a*) OM micrography of alloy A, (*b*) OM micrography of alloy B, (*c*) OM micrography of alloy C, (*A*) SEM micrography of alloy A, (*B*) SEM micrography of alloy B, and (*C*) SEM micrography of alloy C.

B. *Mechanical Properties of the Alloys*

Table IV lists the mechanical properties of alloys A, B, and C. With chromium increasing, the hardness and impact toughness values under the as-cast condition or after heat treatment all increase. The results show that higher chromium content has a good effect on the mechanical properties. The reason is that the increase of chromium not only increases the hardness of boride and hardenability, but also improves the morphology of boride, which is crucial for this kind of material. High boron white cast iron with higher chromium content has a better balance of hardness and toughness and is a somewhat promising wear-resistant material.

V. CONCLUSIONS

1. For high boron white cast iron, with the increase of chromium, the microhardness of boride increases, and the morphology of boride changes from continuous network to less continuous distribution.
2. With the chromium increase, martensite appears in the matrix, and its volume percentage increases. Higher chromium also leads to the uneven distribution of carbon in the matrix, which makes the low-carbon region turn to martensite and the high-carbon region turn to pearlite; the reason for this is that higher carbon favors the $M_{23}(B,C)_6$ particle precipitation.

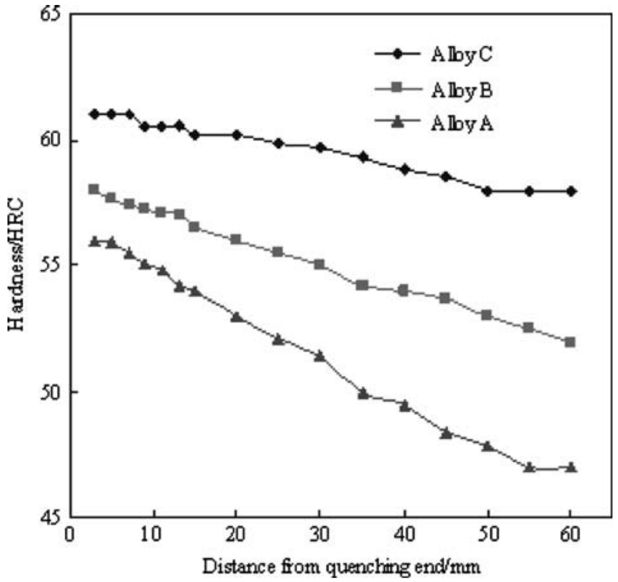

Fig. 6—Effect of chromium on hardenability.

3. A higher chromium content is beneficial to the hardenability; castings of high boron white cast iron with higher chromium can be quenched in air.
4. High boron white cast iron with higher chromium content has a higher hardness and impact toughness and is a somewhat promising wear-resistant material.

Table IV. Mechanical Properties of the Alloys

	As Cast		After Heat Treatment	
Alloy	Hardness/ HRC	Impact Toughness/ J·cm^{-2}	Hardness/ HRC	Impact Toughness/ J·cm^{-2}
A	32.4	9.1	51.4	12.2
B	35.6	10.3	56.5	14.4
C	39.2	13.2	58.6	15.2

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