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Structures and Properties of Cast Irons Reinforced by Trace Addition of Modified SiC Nanopowders†

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(Dated: Received on June 22, 2007; Accepted on October 10, 2007)

To improve the performance of traditional cast iron, trace amount of surface modified nanometer SiC powders were added into the melted iron. The microstructures, the mechanical properties, as well as the wear resistance were investigated. The trace addition of SiC nano-powders were active due to the presence of structural defects arising from the treatment, they were efficient in affecting not only the generation and growth of crystals but also change the morphology of graphite. On the other hand, the addition of SiC nanopowders as heterogeneous seedings in the crystallization of liquid metals lead to the changing of supercooling temperature, so the ratio of ferrite and pearlite was changed. The mechanical characteristics and wear resistance were enhanced as a result of the improved graphite shape and changed matrix composition caused by the trace addition of SiC nanopowders (in amounts of about 0.01% mass). The strengthening mechanism and the free gap between powders were also discussed. It is suggested that the tensile strength, toughness, as well as the wear resistance can be improved simultaneously, which indicates the novel strengthening technology by trace addition of nanopowders is promising to extend to large-scale industrial production.

Key words: Surface modified SiC nanometer powders, Cast iron, microstructure, Mechanical properties, Wear resistance

I. INTRODUCTION

As widely applied traditional materials, cast irons are known for low melting point, good foundry properties, simple smelt technics and low cost, as well as high wear resistance caused by graphite. However, the existence of graphite in the matrix acts as inanition or crack due to its lower strength and toughness, which destroy the continuity of matrix and impair the integrated properties. Recently, metal matrix composites (MMCs) have been proved to be a better choice for improving the properties of iron based material [1-6]. Powder metallurgy method was once used to produce Fe-TiC composite for the advantages of perfect surface quality and precision of products, but they were monolithic composites with a high cost and restricted shape and size [7,8]. From the viewpoint of application, in order to improve the surface wear resistance of components, Wang et al. presented a new cast iron sinter technique to produce iron base surface composites [9-11]. In addition, Hans Berns produced new MMC by hot isostatic pressing (HIP) method and compared it with conventional white cast iron [12].

The typical ceramic SiC particles exhibit the advantages of low cost, high strength and wear resistance. In the class of engineering materials, MMCs containing SiC have received particular interest. However, the selection of matrix is mainly focus on aluminium, only less research on iron matrix has been presented [13-19]. On the other hand, the SiC particle size is usually several micros, with the addition amount of 5%-20% in volume. It is well known that nanometer material has a lot of unique properties, so the addition of nanopowders to iron matrix might play a vagarious role. However, the research about nanopowders additive to cast iron is infrequent.

In the present paper, we report a novel technology of strengthening cast iron by surface modified nanometer ceramic powders in trace amount addition. Foundry method is used to prepare reinforced materials. A brief analysis of microstructures, mechanical properties of reinforced cast irons is carried out, as well as the wear resistance.

II. EXPERIMENTS

A. Materials

The modifier was prepared by the joint mechanical treatment of high-melting disperse synthetic SiC particles with protective metal in a centrifugal planetary mill in an inert atmosphere. Mechanical treatment in an inert atmosphere did not allow the particles to oxidize. Protective metal interacted with high-melting particles, plated them and prevented from coagulation thus pro-

†Part of the special issue from “The 6th China International Conference on Nanoscience and Technology, Chengdu (2007)”.

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DOI:10.1088/1674-0068/20/06/625-631 ©2007 Chinese Physical Society
viding good wetting by the melt.

The gray cast iron HT150, HT250 and nodular cast
iron QT500-7 were used as matrix, which were named
as H1, H2, and Q3 respectively. The compositions of
matrix were given in Table I.

<table>
<thead>
<tr>
<th>Matrix</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1 (HT150)</td>
<td>3.4-3.6</td>
<td>2.0-2.3</td>
<td>0.4-0.6</td>
<td>≤0.4</td>
<td>≤0.45</td>
</tr>
<tr>
<td>H2 (HT250)</td>
<td>3.1-3.3</td>
<td>1.6-1.8</td>
<td>0.7-0.9</td>
<td>≤0.25</td>
<td>≤0.12</td>
</tr>
<tr>
<td>Q3 (QT500-7)</td>
<td>3.6-3.9</td>
<td>2.0-2.8</td>
<td>0.6-0.8</td>
<td>≤0.1</td>
<td>≤0.04</td>
</tr>
</tbody>
</table>

B. Preparation process

The preparation process was as follows: cast iron ma-
trix was melted in induction furnace in vacuum at a
certain temperature. The surface modified SiC nono-
powders at an amount of 0.01%-0.1% mass and particle
size <0.1 micron were packaged by aluminum foil and
placed in the bottom of casting ladle in advance. The
melted liquid metal was poured into the ladle and ho-
mogenized for about 5 min, then poured into a column-
liked sand mold with the dimension of φ30 mm×250
mm. Table II showed the technics parameters of cast-
ing reinforced materials.

C. Microstructure analysis

Microscopic examination of all specimens was studied
by optical microscopy (OM) and Neophot-21 metallur-
gical microscope. The metallography specimens were
etched by 4%HNO₃-ethanol solution.

D. Mechanical testing

In order to quantify the effect of SiC content under
study on its mechanical properties, hardness and ten-
sile strength tests were carried out. The hardness test
was performed on specimens of rectangular cross sec-
tion 30 mm×20 mm×10 mm thickness using Brinell
type hardness tester. The Brinell hardness number was
determined using ball diameter of 10 mm and applied
load of 30 kN. The specimens for the tensile tests were
prepared according to GB 6397-1986 standards. Ten-
sile tests were performed using an Instron tensile test-
ing machine. Each test result reported was the average
from at least three samples from the same location in
the casting.

E. Wear experiment

Wear experiment was carried out on MM200 wear
tester under oil lubrication condition. Ring-Block type
abrasion was employed in present studies. Specimens
were mounted at upper holder, and the mated couple
material T8 steel rotated at a speed of 400 r/min. Ap-
plied loads on specimens were 50, 100, 150, 200, 250,
and 300 N, respectively. The wear time was 60 min in
each cycle. The mass loss of the test specimen was mea-
sured before or after every cycle, and the wear rate was
calculated from the average mass loss over 3 cycles.
Worn surfaces were observed by XL-30 type scanning
electric microscope.

III. RESULTS

A. Microstructure

After the addition of SiC nanoparticles, the struc-
ture of cast iron is distinguished by the morphology of
graphite inclusions. While the unmodified gray cast
iron exhibits a plate-like shape of graphite (Fig.1(a)),
the reinforced sample is characterized by thinner and
shorter flake-like graphite inclusions than unmodified
sample (Fig.1(b)). For the reinforced nodular cast iron,
spherical graphite shape is also improved by the char-
acteristics of smaller radius, more amount, and better
uniformity (Fig.1 (c) and (d)).

After etching by 4%HNO₃-ethanol solution, the mea-
surement results of matrix microstructure indicated
that the ferrite content of reinforced HT150 decreased
and the content of pearlite increased; while the re-
inforced QT500-7 showed the reverse results with in-
creased ferrite content and decreased pearlite content
(Fig.2).

B. Mechanical properties

Figure 3 shows the mechanical properties of cast iron
with different contents of SiC nanoparticles. As the
improvement of SiC nano-powders addition, the ten-
sile strength and the hardness were improved in dif-
ferent degree. When the addition of SiC nanometers

FIG. 1 Optical micrographs with different contents of SiC
nano-powders. (a) H11, (b) H13, (c) Q31, (d) Q34.
TABLE II Chemical composition (wt%) of cast iron

<table>
<thead>
<tr>
<th>Materials</th>
<th>HT150</th>
<th>HT250</th>
<th>QT500-7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H11</td>
<td>H12</td>
<td>H13</td>
</tr>
<tr>
<td>Content of SiC nanopowders/%</td>
<td>0</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Melting temperature/°C</td>
<td>1450</td>
<td>1450</td>
<td>1450</td>
</tr>
<tr>
<td>Casting temperature/°C</td>
<td>1360</td>
<td>1360</td>
<td>1360</td>
</tr>
</tbody>
</table>

FIG. 2 Matrix microstructure with different contents of SiC nanopowders (etched by 4% HNO₃-ethanol solution). (a) H11, (b) H13, (c) Q31, (d) Q34.

FIG. 3 Mechanical properties of gray cast iron. (a) H150, (b) H250.

was 0.1 mass%, the tensile strength was most improved by 22.7% and 8% for HT150 and HT250, respectively.

From the data of Fig.4, the tensile strength and the hardness of QT500-7 were both slightly improved, which indicated that the reinforced effect of SiC nanopowders on nodular cast iron was not as good as gray cast iron. But the shock energy of reinforced samples were improved by 170%, 21%, and 194%, respectively, which indicated the toughness of nodular cast iron was highly improved.

C. Wear resistance results

1. Wear curves

Figure 5 showed the wear results of HT150 and HT250 under oil lubrication. For all the applied load, wear volume of H11 was the most, the wear volume

DOI:10.1088/1674-0068/20/06/625-631 ©2007 Chinese Physical Society
of H12 was decreased by 10%, 20%, 69%, 69%, 78%, and 71%, respectively, while the data of H13 were 33%, 40%, 77%, 75%, 33%, and 47%, respectively. When the load was less than 100 N, all the three specimens represented normal wear condition. As the load reached 150 N, wear volume of H11 increased greatly, which indicated the failure happened. For H12 and H13, the phenomena didn’t appeared until the load reached 250 and 200 N, respectively. The results indicated that the addition of SiC nanopowders improved the bear capability of HT150.

The same improving effect of wear resistance could be seen under all loads. For the same material, the wear volume increased as the increasing of load; for the same load, the wear volume decreased as the increasing of SiC nanopowders content. Among all the specimens, the H24 specimen with 0.1% SiC nanopowders represented the best wear resistance. Under each loads, the wear volume of H24 decreased 80%, 39%, 57%, 71%, and 59%, respectively.

Figure 6 showed the relationships between wear volume and load of QT500-7 with different contents of nanopowders under oil lubrication. When the load reached 250 N, the wear volume of Q31 increased greatly, while the reinforced materials exhibited better wear resistance under all loads. The smallest wear volume was for the Q33 specimen, which indicated the best wear resistance. Under the most load of 300 N, the wear volume of Q33 was only 23% of that of Q31.

2. SEM of worn surface

Under the load of 250 N, both the original H11 specimen and the reinforced H12 material were worn by the abrasive particles, as the SEM images of the worn surfaces showed in Fig.7. The wear grooves of H11 were deeper and wider (Fig.7(a)) than that of H12 (Fig.7(b)). In addition, the tongue-like accumulations appeared in the worn surface of H11, while the phenomena was inconspicuous for the reinforced H12 specimen.

Figure 8 showed the worn surfaces of QT500-7 with different contents of SiC nanopowders under the load of 250 N. A lot of deeper and wider grooves appeared in the worn surface of Q31, while the worn surface of
IV. DISCUSSION

A. Improvement of graphite shape

Due to the use of a well-wetting metal as a protector, SiC nano-powders were easily assimilated under the action of convection flows and uniformly distributed over the melt volume being the nuclei of crystals. Since the introduced nano-powders were also active due to the presence of structural defects arising from the treatment in centrifugal planetary mill, they were efficient in affecting not only the generation and growth of crystals but also change the morphology of graphite. One the other hand, the SiC nanopowders were characterized by high rigidity, better stability and high melting point. When added to the melted iron, the nanopowders acted as exotic cores and increased the forming graphite cores, which was also benefit to improve the graphite shape. Therefore, it can be concluded that the SiC nanopowders took the gestation role, shortened the free growth phase of spherical graphite in liquid state and decreased the possibility of aberrance [20]. As a result, the improved graphite in cast iron decreased stress concentration, so the integrity and strength of matrix were improved [21].

B. Changed ratio of ferrite and pearlite

As shown in Fig.3, ration of ferrite and pearlite was changed after the addition of SiC nano-powders. It is well known that the content of pearlite depends on the supercooling temperature, and the formation of the pearlite structure is characteristic of overheated cast iron. Therefore, the changed ratio is likely to be due to the fact that the addition of SiC nano-powders as heterogeneous seedings in the crystallization of liquid metals leads to the changing of supercooling temperature [22].

C. Improvement of wear resistance

Former research reports considered that the improvement of wear resistance was attributed to the role of SiC particles, because the size and amount of SiC particles used were larger and more. In the contact of wear surfaces, the large and rigid SiC particles supported most load and reduced the loss of matrix. While in the present condition, we attributed the improvement of wear resistance not to the SiC nano-powders themselves, but to the changed matrix microstructures caused by SiC nano-powders.

With the addition of SiC nanopowders, the flake-like graphite with blunt end became thinner and shorter, which strengthened the integrity of matrix. On the other hand, the improvement of hardness decreased the deformation of matrix, and the slight deformation could offset the crack caused by the falling off graphite, which was also benefit to keep the integrity of matrix [23]. The smaller radius and better circularity of spherical graphite weakened the damage induced by stress accumulation, thus improved the integrity of matrix. The better toughness caused by more content of ferrite brought bigger deform space for the matrix under normal load, and the deformed matrix could offset the holes caused by the falling off spherical graphite, which avoided the scratch phenomena. Moreover, the “embossment-like” notch could deposit lubrication oil and strengthen the boundary lubrication role.

D. Technical properties

The advantages of the technology can be summarized as follows: (i) the application of nanometer materials combined with traditional materials; (ii) the addition of trace amount SiC nano-powders to improve the mechanical properties and wear resistance, providing the possibility of replacing the expensive doping metals by relatively cheap disperse synthetic compounds; (iii) relatively economical technology of the casting method used for preparing reinforced materials, extending to the large-scale industrial production.

E. Strengthening mechanism

The presence of disperse phase within the volume of a solid created the conditions for its strengthening affecting the dynamics of dislocations. In this case, such
a material can be considered as disperse-strengthened composite. Poluboyarov et al. explained the strengthening mechanism for the composites reinforced with disperse particles [24]. Under the action of the applied voltage, the sources of dislocations form dislocation loops that surround the particles. The number of dislocation loops $n$ depends on the distance between the particles:

$$n = \frac{l_p \sigma}{G_m |\vec{b}|}$$  

(1)

where $l_p$ is the distance between particles; $\sigma$ is the voltage applied; $G_m$ is the shift module of the matrix material; $\vec{b}$ is Burgers vector of the dislocation. The strain of shift acting on a particle is:

$$\tau = \frac{l_p \sigma^2}{G_m |\vec{b}|}$$  

(2)

and the yield stress of the alloy reinforced by the particles is:

$$\sigma_T = \sqrt{\frac{G_p G_m |\vec{b}|}{l_p C}}$$  

(3)

here $G_p$ is the shift module of the particle material; $C$ is a constant that characterized the alloy type.

Thus, the alloy can be strengthened with disperse particles. The shift module of the particle material $G_p$ should exceed that of the matrix material $G_m$, otherwise strengthening would not occur.

For the alloys with small particle size, the calculation according to the Eq.(3) becomes incorrect. In this case, the shift strain that acts on spherical disperse particles of a size $d$ is determined by the equation:

$$\tau = \frac{2nG_m |\vec{b}|}{d}$$  

(4)

here, the yield stress of the alloy is inversely proportional to the particle size:

$$\sigma_T = \frac{2G_m |\vec{b}|}{d}$$  

(5)

while the particles act as obstacles that hold the movement of dislocation, which means that the dislocation loop is large in comparison with the distance between particles.

So, the theory demonstrates that the yield stress of disperse-strengthened alloys containing coarse particles depends on the strength of both the matrix and the particle material, while at small particle size, the strength of the alloy is directly proportional to the shift module of the matrix and inversely proportional to the particle size.

The major structural parameters that determine the efficiency of particles are the size, as well as the mean free gap between them. In order to determine this value, we shall consider the particles being spherical, and also uniformly and isotropically distributed over the melt volume. Let us draw a sphere around some particle, the radius of this sphere being $R_c$, which is equal to the half of the distance between the centre of this particle and the centre of the neighbouring one:

$$R_c = \frac{d_p}{2} + \frac{l_p}{2}$$  

(6)

where $d_p$ is the diameter of the particle and $l_p$ is a free gap between the particles. The volume $V_c$ of the sphere will include the volume of a particle $V_p$ and the volume of the matrix $V_m$

$$V_c = \frac{\pi}{6} (d_p + l_p)^3$$  

(7)

$$V_p = \frac{\pi}{6} d_p^3$$  

(8)

$$V_m = \frac{\pi}{6} (d_p + l_p)^3 - \frac{\pi}{6} d_p^3$$  

(9)

Then, introducing relative particle volume, (volume content of particles):

$$V_p' = \frac{V_p}{V_p + V_m}$$  

(10)

and having made the corresponding transformations in Eq.(9) we obtain:

$$l_p = \frac{d_p \left(1 - \frac{1}{\sqrt{V_p'}}\right)}{\sqrt{V_p'}}$$  

(11)

The corresponding distance between the centres of particles $l_c = 2R_c$ will be expressed as:

$$l_c = (V_p')^{-1/3}$$  

(12)

The movement of dislocations in the matrix with nanopowders will be possible if the applied strain is sufficient to curve a dislocation into a semi-round loop. The smallest curvature radius of the dislocation under the action of internal strains $\tau$ can be determined from the equation:

$$R_{\text{np}} = \frac{G_m |\vec{b}|}{2\tau}$$  

(13)

where $R_{\text{np}} = l_p/2$.

The strain $\tau$ required to bend the dislocation between the particles is determined according to Eq.(12) as follows:

$$\tau = \frac{G_m |\vec{b}|}{l_p}$$  

(14)

In order to estimate the range within $l_p$ changes, let us use the yield stress of matrix $\tau_m = G_m/1000$, as a

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minimum strain required for pressing the dislocation between the particles. We shall take the maximum stress equal to the theoretical shift strain of the matrix \( \tau_c = G_m / 30 \) for face-centered cubic lattice of metals and \( \tau_c = G_m / 10 \) for body-centered cubic lattice of metals. Having substituted the latter figures and Burgers vector \( \| b \| = 0.3 \text{ nm} \) into the Eq.(13) we come to the result that in order to provide efficient strengthening of the metal, the free interparticle gap should be within the range 0.01-0.3 \( \mu \text{m} \) for fcc metals and 0.003-0.3 \( \mu \text{m} \) for bcc metals.

Thus, the analysis allows to conclude that a new class of nanopowders is introduced into metals and to consider the technology of strengthening modification as one of the most promising fields.

V. CONCLUSION

The investigation of strengthening cast iron by surface modified SiC nanopowders in different contents leads to the following conclusions:

(i) The addition of SiC nano-powders improved the graphite shape. The flake-like graphite was thinner and shorter with blunt ends, while the spherical graphite was with the characteristics of smaller radius, better circularity and more amount.

(ii) The microstructure of matrix was changed by the addition of SiC nano-powders. For gray cast iron, the content of ferrite decreased and the content of pearlite increased; while for nodular cast iron, the content of ferrite increased and the content of pearlite decreased.

(iii) The wear resistance of cast irons were improved. The prime contents of SiC nano-powders were 0.1% and 0.05% mass for gray cast iron and nodular cast iron, respectively. The enhanced wear resistance was attributed to the improvement of graphite shape and the changed ratio of ferrite/pearlite in the matrix.

(iv) The data presented conclude that the application of modified nanopowders is promising for the strengthening of traditional cast irons.