The forty years of vermicular graphite cast iron development in China (Part 1)

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Abstract: In China, the research and development of vermicular graphite cast iron (VGCI) as a new type of engineering material, were started in the same period as in other developed countries; however, its actual industrial application was even earlier. In China, the deep and intensive studies on VGCI began as early as the 1960s. According to the incomplete statistics to date, more than 600 papers on VGCI have been published by Chinese researchers and scholars at national and international conferences, and in technical journals. More than ten types of production methods and more than thirty types of treatment alloy have been studied. Formulae for calculating the critical addition of treatment alloy required to produce VGCI have been put forward, and mechanisms for explaining the formation of dross during treatment were brought forward. The casting properties, metallographic structure, mechanical and physical properties and machining performance of VGCI, as well as the relationships between them, have all been studied in detail. The Chinese Standards for VGCI and VGCI metallographic structure have been issued. In China, the primary crystallization of VGCI has been studied by many researchers and scholars. The properties of VGCI can be improved by heat treatment and addition of alloying elements enabling its applications to be further expanded. Hundreds of kinds of VGCI castings have been produced and used in vehicles, engines, mining equipment, metallurgical products serviced under alternating thermal load, machinery, hydraulic components, textile machine parts and military applications. The heaviest VGCI casting produced is 38 tons and the lightest is only 1 kg. Currently, the annual production of the VGCI in China is about 200 000 tons. The majority of castings are made from cupola iron without pre-treatment, however, they are also produced from electric furnaces and by duplex melting from cupola-electric furnaces or blast furnace-electric furnace. Examples of typical applications for VGCI castings are introduced in this paper. In China, the technologies such as rapid testing of the molten metal and non-destructive testing of casting microstructure still need to be improved. Several proposals are put forward in this paper in order to improve the production of VGCI. Generally speaking, in China, the research, production, and application of vermicular graphite cast iron are at the same level as in other developed countries and in some fields China even takes lead. (332 references and 5 Tables)

Key words: vermicular graphite cast iron; China; review

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1. Brief introduction to VGCI development in China

The earliest report on vermicular graphite (VG), was in Morrogh’s paper in 1948. He found ‘thick flake graphite’ (i.e. vermicular graphite), during his study of spheriodal graphite cast iron (SGCI), treated with cerium. However at that time VG was considered a failure with no practical application. The breakthrough for VG was made in the 1960s: R. D. Shelleng of the American International Nickel Co. obtained a British patent (1069058) and an American patent (3421886) for the production of VGCI using magnesium-titanium alloy; later, Austrian W. Thury et al, obtained an Austrian patent (290592) for the production of VGCI using mischmetal. In 1976, with an improved formula developed by BCIRA, the American International Nickel Co. produced and marketed ‘Foote’ alloy; since then VGCI has been developed relatively quickly [1-4].

In China, knowledge of VG also occurred with the production of SGCI, especially in the early 1960s, when SGCI was made using Rare Earth (RE) ferrosilicon alloy, and vermicular graphite appeared quite often. As in other foreign countries, this type of graphite was considered as a ‘black spots’ defect in China. Mr QIU Han-quan of the Shandong Institute of Mechanical Design and Research deliberately studied iron containing this kind of graphite as a new type of engineering material. From 1965, he treated liquid iron with RE alloy and used the resulting iron to replace high strength GCI in Jinan’s Materials Test Machinery Plant and Jinan’s Machine Tool Foundry [5, 6].

Nevertheless, in China VGCI was not developed from bad SG iron, but due to the following two factors:

(1) Early in 1965, when the authors added RE alloy to high

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carbon liquid iron, it was found that some ‘black spot’ occurred in the fracture of samples and the tensile strength of the iron exceeded grade 300 GCI. At that time, due to the shortage of scrap steel, using RE to directly treat cupola iron without the addition of scrap steel to obtain high grade GCI, became important.

(2) From 1967, considering the beneficial effect of RE in improving the mechanical properties and the shortage of scrap steel supply in China, some foundries were making machine tool castings tried to add RE alloy into high carbon molten iron to obtain high grade GCI. During these experiments it was found that the iron with vermicular graphite had high strength; thus high strength GCI was obtained without the addition of scrap steel [8, 9].

Since the above high strength GCI was obtained using RE alloy, it was called RE high strength GCI [9], RE high grade GCI [10], RE 40-68 GCI [11], RE GCI [8, 12], RE ‘thick flake graphite’ GCI [14, 15], and compacted graphite iron [16, 17] etc. At the end of 1970s, according to the two-dimensional morphology of the graphite, this iron was called vermicular graphite cast iron (VGCI) in the national and international literature [18]. In 1979, at the national conference on RE, the author suggested that vermicular graphite cast iron was called VGCI for short [19].

During research, the author found that for flake graphite to change to vermicular graphite, there is a critical addition of RE; above this critical addition the mechanical properties will change significantly. An equation for the critical addition was formulated and Tables 1 and 2 list the critical addition based on this equation [10, 11, 20]. This addition rate was utilized for stable production of VGCI in China.

### Table 1 The critical treatment alloy addition for obtaining VGCI, wt. %

<table>
<thead>
<tr>
<th>Base metal sulphur</th>
<th>Calculated pure RE addition</th>
<th>Equivalent addition of RE ferrosilicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03</td>
<td>0.176</td>
<td>0.82</td>
</tr>
<tr>
<td>0.04</td>
<td>0.210</td>
<td>0.98</td>
</tr>
<tr>
<td>0.05</td>
<td>0.246</td>
<td>1.14</td>
</tr>
<tr>
<td>0.06</td>
<td>0.280</td>
<td>1.31</td>
</tr>
<tr>
<td>0.07</td>
<td>0.315</td>
<td>1.47</td>
</tr>
<tr>
<td>0.08</td>
<td>0.35</td>
<td>1.63</td>
</tr>
<tr>
<td>0.09</td>
<td>0.384</td>
<td>1.79</td>
</tr>
<tr>
<td>0.10</td>
<td>0.424</td>
<td>1.97</td>
</tr>
<tr>
<td>0.11</td>
<td>0.482</td>
<td>2.15</td>
</tr>
</tbody>
</table>

* The above two tables are based on approximately 21.5 % RE content and should be taken only as a reference for different melting conditions.

Similar to SG iron production, a large amount of dross is formed after treatment of VGCI. This became one of obstacles for expanding the application of VGCI. The author published a paper on formation mechanism of the dross [21]. Based on the mechanism RE-zinc-alloy was invented and the dross problem was solved; other methods based on these principle also produced good results.

It is seen that in China, the research, development and application of VGCI were started in the same period as in other developed countries, but its actual industrial applications were even earlier than in other countries. This was demonstrated from the appraisal conclusion on the research program of the fifth 5-year plan: ‘Making VGCI using cupola iron’ carried out by the Shandong Institute of Mechanical Design and Research and Shandong Material Test Machinery; the appraisal meeting was organized by the first Ministry of Industry and Research and Shandong Material Test Machinery; the ‘VGCI Standard of Chinese Ministry of Railway (TB/T 2444-93)’ was also issued in the 1990s, for applications in the railway industry. The Collection of Chinese Vermicular Graphite Cast Iron Papers, edited in 1987, contains more than 351 technical papers [22]. After completing the research projects on VGCI in the national fifth, sixth and the seventh 5-year plan, the research and application of VGCI have been further developed. Generally speaking in China, the research, production, and application of VGCI are at the same level as in other developed countries; in some fields China even takes the lead.

Between the late 1960s and late 1980s, VGCI was used in small volume production trials for hydraulic components in milling machine M114, universal milling machine M131W [20, 21, 24], internal grinder M210 and external grinder M211 [10, 23, 24], large horizontal boring machine Y58 [19, 160 t horizontal borer [29, 26], medium and large hydraulic presses [18]. In addition VGCI was used in thin wall castings for engines; for example, the engine cylinder block and head, flywheel, connecting plate, cylinder liner etc [31-33]. Good results were also obtained using VGCI for butterfly valves, scrapers in sand mixer, rolls of sand mills and paper machines [17, 34-35]. The application of VGCI was expanded to more than 200 components from more than 60 manufacturers in various industries including machinery manufacturing, mining, metallurgical, transportation, light industry, textile and defense industries and showed very good technological and economical results. The heaviest vermicular graphite iron casting produced is 38 tons [9], and the lightest is only 1 kg [20]. Most of the VGCI was made directly from cupola iron with a small amount made from electric furnace or duplex melting of cupola-electric furnace; a small number of VGCI castings were even made directly from blast furnace iron.

After more than twenty years study and application, experience and expertise have been accumulated for producing...
VGCI, especially using cupola melted poor quality iron. Some of them have been written and included in the university text books. There is a separate chapter of VGCI in the Chinese ‘Cast Iron Handbook’ and other manuals.

In the last ten years, due to rapid economic development, the increased high demand for engines and metallurgical equipment castings, normal grey cast iron (GCI) can not satisfy the requirement of the development; while VGCI shows the special advantages and has been developed very fast. Currently in China the production of VGCI is about 200 000 tons. Nevertheless some problems still exist and influence the development of VGCI.

However the enhancement and development of VGCI have been influenced in China due to following reasons:

1. Due to lack of knowledge and understanding of the advantages, VGCI is still considered as a solution only for solving the shortage of steel scrap. Therefore the production of VGCI is sensitive to the supply of scrap steel.

2. In China, generally the good quality of raw materials is very difficult to ensure (this is a key problem), the melting furnaces are simple, and the quality of liquid iron is poor (low temperature and high and inconsistent sulphur content); production sites are lack of quick, accurate test and control measures. All these result in inconsistency of VGCI production, especially, it is very difficult to accurately control the high percentage of vermicular graphite (>90%) obtained in thin wall castings.

In recent years the application of VGCI in Europe and North America has developed very rapidly. VGCI as a new engineering material has been used in safety critical castings, for example engine blocks. The draft European standard for VGCI has been completed and the formal standard will be issued later this year. In this standard, the percentage of VG should be > 80% in main wall sections of the casting; in other sections VG can be lower than 80%. No flake graphite is allowed in any section of the casting. In Sweden, for obtaining the special properties in the piston rings, the minimum VG specified is >90%. From 2003, USA has separated the production of VGCI from that of SG iron.

The more rapid development of VGCI in western countries is due to the higher and higher requirements for powertrain and parts for the automotive industry. As the special power ratio (kW/litre) of engines becomes higher and higher, the operating temperature becomes higher and higher. Aluminium alloy cannot withstand the increased loads and VGCI is the best solution to the problem; VGCI has strength close to SG iron, damping capacity, thermal conductivity and casting properties are all similar to GCI, plasticity and thermal fatigue are much better than GCI. The weight per unit power of a VGCI engine is lower than that of an aluminium engine. In addition, the production process from metal ore to finished casting, the energy consumption of VGCI is less than that of aluminium. All this promotes the development of VGCI.

In China, it can be seen that although rapid development in the production of VGCI has occurred, the gap in the percentage control of VG and standards between China and other developed countries is large. This needs attention for Chinese foundrymen and scholars.

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