Effect of alloying elements W, Ti, Sn on microstructure and mechanical properties of gray iron 220

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Abstract: Experiments were carried out to observe the variation in microstructure and mechanical properties of gray cast iron by adding pearlite promoting alloying elements such as Ti, Sn and W. Results show that adding Sn, Ti, and W with different concentrations improve the microstructure, Brinell hardness and tensile strength of gray cast iron. With the increase of alloying element concentration, the average graphite length and graphite content increase linearly. At the same time, average cell size and the maximum graphite length also decrease linearly. Brinell hardness and tensile strength of gray cast iron also increase with an increase in alloying elements contents, and attain the maximum when Ti = 0.561%, Sn = 0.561% and W = 0.945%. However, at higher concentrations of Ti = 0.810%, Sn = 0.631% and W = 1.351%, the tensile strength decreases from 333 MPa to 297 MPa and the Brinell hardness decreases from 248 HB to 225 HB. The decrease in tensile strength and Brinell hardness at the higher concentration level is attributed to the formation of coarse and thick graphite flakes.

Key words: gray cast iron; tin; titanium; tungsten; mechanical properties

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Gray cast iron is being widely used in the industrial market due to its low price and excellent properties such as low melting temperature, minimum shrinkage, deformation resistance and corrosion resistance^[1,2]. Over the past decade, more than 70% of the world's cast materials are gray cast iron^[1]. However, gray cast iron has poor tensile strength, high brittleness and high density compared with new iron alloys. These disadvantages may hinder the use of gray cast iron in many specific applications^[2]. However, the tensile strength can be improved through optimum selection of iron compositions, casting method, and sintering phenomenon^[3]. Recently, the tensile strength of gray cast iron has been improved significantly by adding small amounts of alloying elements to the iron's matrix to control the microstructure. These alloying elements are

titanium (Ti), tin (Sn) and tungsten (W). The addition of these carbide forming elements "TiC, SnC and WC" also play a vital role to improve the microstructure, hardness and tensile strength of the gray cast iron^[4].

It was observed that Ti in gray iron may increase the super cooling degree and therefore promote the growth of D-type graphite, significantly improving tensile strength. The higher value of Ti in gray iron may also improve the thermal shock resistance by suppressing the nitrogen effect^[5]. Similarly, Sn is considered an active pearlite promoter as stability of pearlitic matrix has been observed in gray iron without forming the massive cementite. Sn has no influence on depth of chilling except at a higher concentration. Although the use of Ti and Sn in gray cast iron improves the tensile strength^[6], it gets saturated at a higher concentration of Sn and Ti, and tensile strength starts to decline while hardness shows the rising trend even beyond the declining point of tensile strength^[7].

Consequently, gray cast iron alloyed with Sn and Ti is highly weighted with limited improvement in tensile strength as compared to hardness, therefore it is a challenging task for scientists and engineers to

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improve the tensile strength and hardness in the same trend with controlled weight of the final product^[8].

Tungsten (W) is an alloy with high tensile strength and hardness and is currently being used in many structural applications. It has also been reported that W addition in gray cast iron^[9] significantly improves the tensile strength by increasing pearlite microstructure^[10]. Therefore, the combination of Ti, Sn and W alloys with controlled weight can be very useful to improve the tensile strength of gray iron.

The aim of this study is to improve the microstructure and mechanical properties of gray cast iron by adding alloy elements W, Sn and Ti. The graphite flakes, hardness, and tensile strength of gray cast iron are evaluated.

1 Experimental procedure

To prepare the tensile test samples, a green sand mould is prepared, which composition is as follows: green sand 63.5%, bentonite 20%, coal dust 12%, yellow dextrin 1.5% and water 3%. The sand mould mixture is mixed in a muller for 4 min. The moulds are prepared in a moulding box of mild steel to achieve the sample size of 30 mm in diameter and 200 mm length. The moulds are coated with liquid carrier “spirit-based” (isopropyl alcohol) coating^[11], and then, were baked at 200 °C for 8 min under CO₂ gas flow. Finally, the moulds were cooled down at room temperature and cleaned with high pressure air.

The gray cast iron is manufactured in 10 kg high frequency induction furnace (16 kW power) with acid refractory lining and cooling coils with cooling water circulation. W powder (99.9% purity, 14.5 µm), Sn powder (99.9% purity, 9.5 µm) and Ti powder (99.9% purity, 22.4 µm) were added as alloying elements. Ferrosilicon with size less than 3 mm and 0.5% of the total charge was used as an inoculant. The silicon content is 60% in Fe-Si.

Firstly, the gray cast iron UK grade 220, labelled as sample

A, was manufactured by induction furnace then held inside the furnace at 1,550 °C for 15 min. Hereafter, the molten metal in a pre-heated ladle (i.e., reddish in appearance) was tapped and stirred continuously at 1,500 °C to ensure the homogeneity of inoculant. Then it was vertically poured into a mould at 1,450 °C.

Sample A at this stage served as the matrix material for the preparation of Samples B, C and D. Later, the poured sample was cooled overnight and collected for the respective analyses. Further, Samples B, C and D were manufactured by mixing various compositions of Sn, W and Ti powders with the Sample A matrix, as displayed in Table 1. Then the samples were heated to 1,880 °C, the required amount of W powder was added, and holding for 15 min. After that, they were tapped into a pouring ladle at 1,790 °C, gently stirred to ensure the homogeneity of inoculant, and the desired Ti and Sn powders were periodically added into it. Finally, the molten iron from the ladle was vertically poured into a similar mould as was used for Sample A. The total time from tapping to pouring was about 10 min for all the samples.

The dimensions of the sample for tensile testing are shown in Fig. 1. The samples required for hardness and metallographic testing are cut from the broken tensile test samples.

Fig. 1: Dimensions of tensile testing bars

The samples for microstructure observation were ground, polished and etched with 2% nitric acid alcohol solution. The sample size was 20 mm thick and 30 mm in diameter. Optical microscopy (MR-6000) was used for microstructural analysis. The composition of the gray cast iron was measured by a spark emission spectrometer with SEM and the results are shown in Table 1.

Table 1: Composition of base metal with and with-out alloying elements W, Sn and Ti (wt.%)

Sample	C	Si	Mn	P	S	Sn	Ti	W
A	3.479	2.127	0.475	0.052	0.131	0	0	0
B	3.512	2.458	0.640	0.055	0.118	0.253	0.350	0.741
C	3.515	2.508	0.640	0.067	0.140	0.473	0.561	0.945
D	3.518	2.565	0.640	0.082	0.142	0.631	0.810	1.351

Tensile strength testing was performed with the help of a universal testing machine at a loading rate of 10 mm·min⁻¹. The yield strength and tensile strength are the average values of three measurements.

For the Brinell hardness experiment, the disc shaped disc samples with thickness of 10 mm and diameter of 15 mm were prepared according to TS EN 6506-4 201. The sample surface was ground to remove the residual contents. Brinell hardness was measured by indentation steel ball with diameter of 10 mm and load of 3,000 kg.

2 Results and discussion

2.1 Microstructure

Figure 2 shows the metallographies of base iron with and without chemical etching. The microstructure is composed of pearlite matrix and graphite flakes. The graphite flakes are evenly distributed, but the direction is random^[12], and they are determined to be A-type graphite^[13].

The microstructures of Sample B, with and without etching, are shown in Fig. 3. These microstructure images demonstrate

Fig. 2: Microstructures of Sample A without (a) and with (b) chemical etching

Fig. 3: Microstructures of Sample B without (a) and with (b) chemical etching

the Type D graphite along with reference Type A graphite. It can be observed that from the microstructure morphology, the Type A graphite is dominated on Type D graphite^[14]. After adding a small amount of Sn, Ti and W into the matrix, new graphite flakes appear in the "interdendrite" of the pearlite matrix, showing obvious segregation but random direction. Ti in an alloy controls solidification and promotes segregation of microstructure^[15]. Therefore, the formation of super cooled D-type graphite flakes are related to Ti^[16].

The metallographic observation of Sample C shows existence of A- and F-type graphite flakes (Fig. 4). Many factors such as moisture, contamination, and rate of cooling

can result in the generation of F-type graphite flake. The moisture and contamination is constant in all heats, but only cooling rate increases linearly with the addition of Ti and Sn alloys. This can be the reason for the generation of F-type of graphite flake. Furthermore, the flake graphite structures in Sample C also show A- and F-type graphite with maximum and minimum strength in both Mn sequences^[14], as shown in Fig. 4. It was observed that Mn sequence in sample C was different for both A- and F-type structures^[17].

The microstructures of Sample D (Fig. 5) shows both A- and E-type graphite. The E-type graphite is composed of interdendritic segregation but with preferred orientation. It is

Fig. 4: Microstructures of Sample C without (a) and with (b) chemical etching

Fig. 5: Microstructures of Sample D without (a) and with (b) chemical etching

also reported that E-type graphite flake occurred at high under-cooling during metal solidification and can be associated with D-type graphite. It is also reported that the E-type graphite occurred at a high Sn value in gray cast iron [6].

Conclusively, the reference Sample A shows the graphite Type A, however after adding the Ti, Sn and W in gray cast iron, the Types D, F and E graphite along with A-type graphite are generated. On the basis of the pearlite promoting and chilling predisposition properties of Sn [18], Ti and W alloys, significant improvement was observed in the microstructure of the gray cast iron, which results in degenerate graphite forms subsequent from Ti, Sn and W mediations (Fig. 3–5).

The graphite length, graphite content, grain size, pearlite and ferrite area fraction of all casting bars were measured by software ImageJ. The summary of area fraction of all casting bars is described in Table 2. We have measured the interdendritic arm spacing between the two closed arm axes and length of graphite based on three curved graphite flakes which are longest in the

selected area [19]. Measurements are conducted on three images of each microstructure with almost 400–600 objects, i.e., lamellas per image. The graphite particles acquired an average length of graphite line 100–200 μm and we have observed the average curved graphite particle 50% for all manufactured samples. Most of them show the A-type graphite including a small amount of the F-type, E-type and D-type graphite [20], as shown in Figs. 2–5. Moreover, the gray cast iron morphology and distribution of the pearlite territory incorporation in these gray cast irons is also apparently dissimilar. In Samples A and B, the pearlite lamellas are coarse as compared to Sample C. Some of them are even larger with an average inter-lamellar spacing of 3–4 μm , as shown in Figs. 4 and 5. We have measured the length of ferrite region ranging from 100 to 200 μm in the pearlite matrix. As ferrite has poor mechanical performance, the abundance of the ferrite regions in the pearlite matrix can decline microstructure and mechanical properties of the gray cast irons in Sample D [21].

Table 2: Microstructure analysis of gray cast iron Samples A, B, C and D

Sample	Structure type	Graphite content (%)	Average graphite length (μm)	Max graphite length (μm)	Average particle size (μm)	Pearlite/Ferrite (%)
A	Type A	10.8 $\pm$ 1.4	34.1 $\pm$ 2.5	411	398 $\pm$ 31	68/32
B	Type A+D	11.5 $\pm$ 1.2	35.4 $\pm$ 2.8	395	394 $\pm$ 27	65/35
C	Type A+F	11.4 $\pm$ 1.6	36.5 $\pm$ 3.2	355	385 $\pm$ 25	62/38
D	Type A+E	11.8 $\pm$ 1.3	37.1 $\pm$ 2.8	324	371 $\pm$ 21	59/41

The alloying elements Sn, Ti and W affect the graphite morphology and distribution of gray cast iron [22]. Sn [14] and Ti may be more effective, because both interact synergistically with gray iron to refine pearlite, to improve the penchant of graphitization, and the size of the graphite flake also becomes smaller because of the two elements' direct effect on the pearlite and ferrite. The absence of ferrite microstructure improved the Brinell hardness and tensile strength of the gray cast iron. It can be seen from the graph trend [Fig. 6 (a and b)] that the graphite contents (%) and the average graphite lengths almost linearly increase with the doping

of alloy elements, which may be due to the high carbon content.

2.2 Ultimate tensile strength

Mechanical properties of gray cast iron containing different Sn-Ti-W contents are shown in Table 3. The results of ultimate tensile strength for Samples A, B, C and D are shown in Fig. 7. There is no apparent difference in the ultimate tensile strength value of reference Sample A and Sample D. Sample C presents higher ultimate tensile strength and low yield strength compared to Sample B due to the corresponding pearlite matrix and

Fig. 6: Average and max. graphite length (a); percentage of graphite content and average particle size (b) in different gray cast irons

Table 3: Measured results of Brinell hardness, yield strength and UTS for Samples A, B, C and D

Sample	Brinell hardness (BHN)	Yield strength (MPa)	UTS (MPa)	Trace element (%)
A	196	203	299	Reference sample
B	215	245	324	Sn 0.473, Ti 0.561, W 0.741
C	248	241	333	Sn 0.631, Ti 0.816, W 0.942
D	225	192	297	Sn 0.897, Ti 1.045, W 1.315

Fig. 7: Influence of W, Ti, and Sn on ultimate tensile strength of Samples A, B, C and D

Fig. 8: Influence of W, Ti, and Sn on hardness, tensile strength and yield strength of Samples A, B, C and D

superior graphite flakes compared to Samples A and B^[23]. These alloying elements strengthen and superfine the graphite flakes, and consequently increase the ultimate tensile strength and yield strength^[24]. The decrease of tensile strength and yield strength of Sample D may be attributed to irregular, thick, coarse lamella and abundance of graphite in matrix composition. Graphite morphology plays a key role in improvement of the graphite flakes' growth rate; therefore, the best mechanical properties were obtained in Sample C.

2.3 Brinell hardness

For the Brinell hardness test, three points were made on each sample and the average was taken. The values are shown in Table 3.

Figure 8 shows a gradual increasing of hardness values up to Sample C followed by a sharp decreasing for Sample D. The decrease of the Brinell hardness may be attributed to the increased quantity of the soft flake on the microstructure of the sample D. It is also observed that hardness value is inversely proportional to indentation depth. The indentation depth of gray cast iron decreases with the addition of Sn, Ti and W^[25].

The existence of flake graphite and pearlite structure in the sample is the main factor to improve the hardness. The hardness value of Sample D decreased compared with that of Sample C, which is caused by the thickness and irregularity of graphite layer in the structure and the increase of graphite content.

3 Conclusions

We have studied the effects of Ti, Sn and W on the microstructure and mechanical properties of gray cast iron. Based on the experimental results, we can draw the following conclusions:

(1) The product was manufactured under industrial conditions and it achieved controlled weight as well as improved tensile strength in similar trend with hardness.

(2) At higher concentrations of Ti, Sn and W, the mechanical properties are decreased due to its high graphite content, high free carbon, and coarse and thick graphite flakes.

(3) The gray cast iron is characterized by Type A graphite flake while under the influence of Ti, Sn and W, the A-type of graphite transformed into D-, F- and E-graphite flakes. The D- and E-type of graphite may occur at high cooling rates due to the influence of Ti and Sn. The occurrence of F-type graphite flakes may need further study to confirm its formation.

(4) The average particle size and graphite length decrease with the increasing of Ti, Sn and W ratios.

(5) W plays an important role in improving tensile strength.

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