CAUSES OF VARIATION IN PROPERTIES OF CASTINGS CONFORMING TO BS4844: 1986 GRADE 3D HIGH CHROMIUM WHITE CAST IRON

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Abstract

High chromium iron castings have been observed to exhibit significantly varying mechanical properties. To establish the origin of inconsistencies in properties, the research was conducted in two phases. First, monitoring to maintain consistency of charge materials and pouring temperature in order to eliminate extraneous operational variables from causative factors. Second, microstructural variations and consistency in mechanical properties were characterised and compared for different heats with small deviations in chemical compositions within the specification BS4844:1986 Grade 3D of high chromium white cast iron. The investigation revealed that marked inhomogeneity of microstructure as a result of variation in particularly chemical composition as well as operational parameters such as inconsistencies in pouring temperatures. The solution to this problem lies in narrowing the specification range by raising the lower limits to 2.5% C and 25% Cr, as well as controlling the pouring temperature to around 1550ºC and reducing solidification time as much as possible.

Keywords: Chromium iron, variation, mechanical properties

1.   INTRODUCTION

High chromium white cast iron is used extensively in the heavy duty rugged abrasion-percussive rock crushing in mining and construction industries. For such applications, wear and abrasion resistance is a critical property, which is exhibited by BS4844:1986 Grade 3D. However, the wide variation in mechanical properties of high chromium white iron castings despite conforming to the chemical specification has been a cause for concern among users in South Africa and beyond. In bid to solve the recurrent customer complaints the goal of this paper is to investigate the causes of inconsistences in mechanical properties of castings. The findings will provide technical data to solve the problem faced by producer foundries.

2.   LITERATURE REVIEW

High chromium iron has been found to be a suitable material for such an aggressive applications such as minerals processing, quarrying where abrasive wear is required. The chemical composition is slightly hypo-eutectic falling short of full eutectic of austenite and carbide resulting in an as-cast microstructure consisting of dendrites of primary austenite in the eutectic mixture of austenite and $(Cr, Fe)_7C_3$ carbides. The abrasion (or wear) resistance of high chromium white cast iron depends on the type of carbide, as well as its hardness, morphology, distribution and volume fraction. The orientation of the eutectic and precipitated carbides is also determining [1]. It is essential to note that the type M_7C_3 carbides are more preferable to any other types such as M_3C, $M_{23}C_6$ (i.e. $Cr,Fe)_{23}C_6$ and M_6C, which tend to be coarse and continuous. Ideally, primary austenite should be surrounded by the eutectic of discontinuous $(Cr, Fe)_7C_3$ carbides. The other carbide forms tend to appear with increasing M:C ratio [2]. Manganese plays a role in refining austenite and preventing pearlite formation [3]. A suitable morphology of austenite (γ) in a eutectic mixture of $γ/M_7C_3$ can be obtained through subsequent heat treatments [4]. High chromium white cast irons have been widely used for abrasion resisting applications, where good abrasion resistance is attributed to high content of eutectic carbides [5].

Depending on the chemical composition of the melt, solidification of high chromium white cast irons begins with the formation of primary phase *i.e.* austenite in hypoeutectic alloys (or primary $(Cr,Fe)_7C_3$ in hypereutectic alloys) followed by the eutectic phase of $\gamma + (Cr,Fe)_7C_3$. Alloys of eutectic composition solidifies with eutectic cellular structure ($\gamma + M_7C_3$) [5]. It has been also found that the solidification of 27% Cr cast iron starts at 1538K (1265°C) with the formation of pro-eutectic austenite, followed by the mono-variant eutectic reaction ($L \rightarrow \gamma + (Cr,Fe)_7C_3$) [6]. The carbide volume can be calculated from equation 1:

% carbide volume = 12:33(%C) + 0:55(%Cr) - 15.2 (1)

The typical phases in the microstructures of as-cast high chromium white cast iron are shown in **Figure 1**. The microstructure consists of primary austenite dendrites surrounded by a eutectic consisting of austenite and carbide of type M_7C_3 [4] in this case the carbide constituent in the eutectic is $(Cr,Fe)_7C_3$.
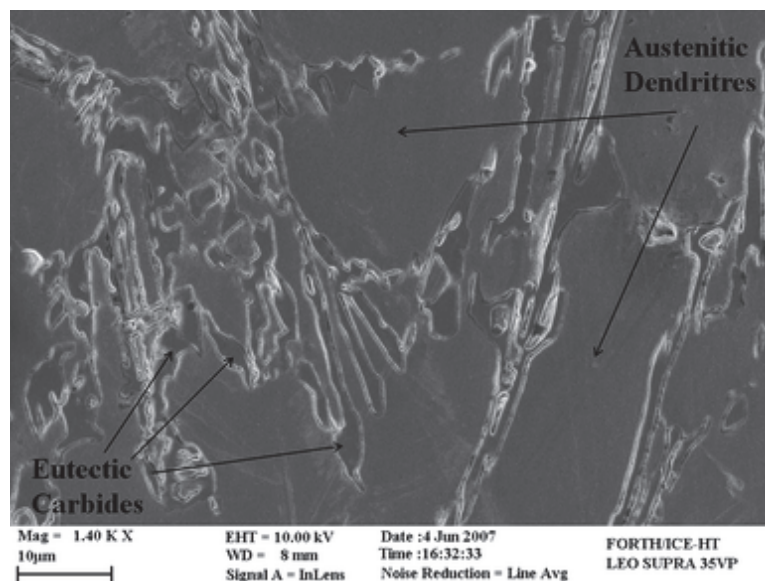

Figure 1 The micrograph of as-cast high chromium white cast iron [4]

The volume fraction of pro-eutectic austenite is determined by how far the composition of the alloy is from eutectic. The closer the composition is to eutectic the lower fraction of primary dendrites of austenite and vice versa. In other words, as the composition approaches the eutectic, the higher volume fraction of eutectic relative to primary austenite. The abrasion resistance originates also from work hardening that follows plastic deformation of austenite as a result of surface working. However, excessive impact may actually cause complete failure of component [7]. Thus, for high impact loading, the as-cast high chromium white cast iron may not perform well because of possibility of fracture. Castings are heat treated to tempered martensite while making an effort to keep retained austenite as low as possible to prevent its deleterious effects such as spalling [8].

The eutectic composition has been found to be approximately 2.8 % C and 26.4 to 28 % (Cr) [9], which means that for compositions below eutectic, primary austenite solidifies out of liquid while the composition of remaining liquid gets progressively enriched with C and Mn solutes until the eutectic composition is reached, where the eutectic reaction occur as alternate solidification of austenite and $(Cr,Fe)_7C_3$ carbide, hence the final microstructure of primary austenite in the matrix of eutectic. In applications where relatively modest impact strength is required, the as-cast condition performs adequately.

Figures 2 (a), (b), (c) and (d) illustrate a wide range of microstructures of as-cast high chromium white cast iron conforming to BS4844:1986 Grade 3D chemical specification. The topology and morphology of the phases in the microstructure will have a bearing on the mechanical properties.
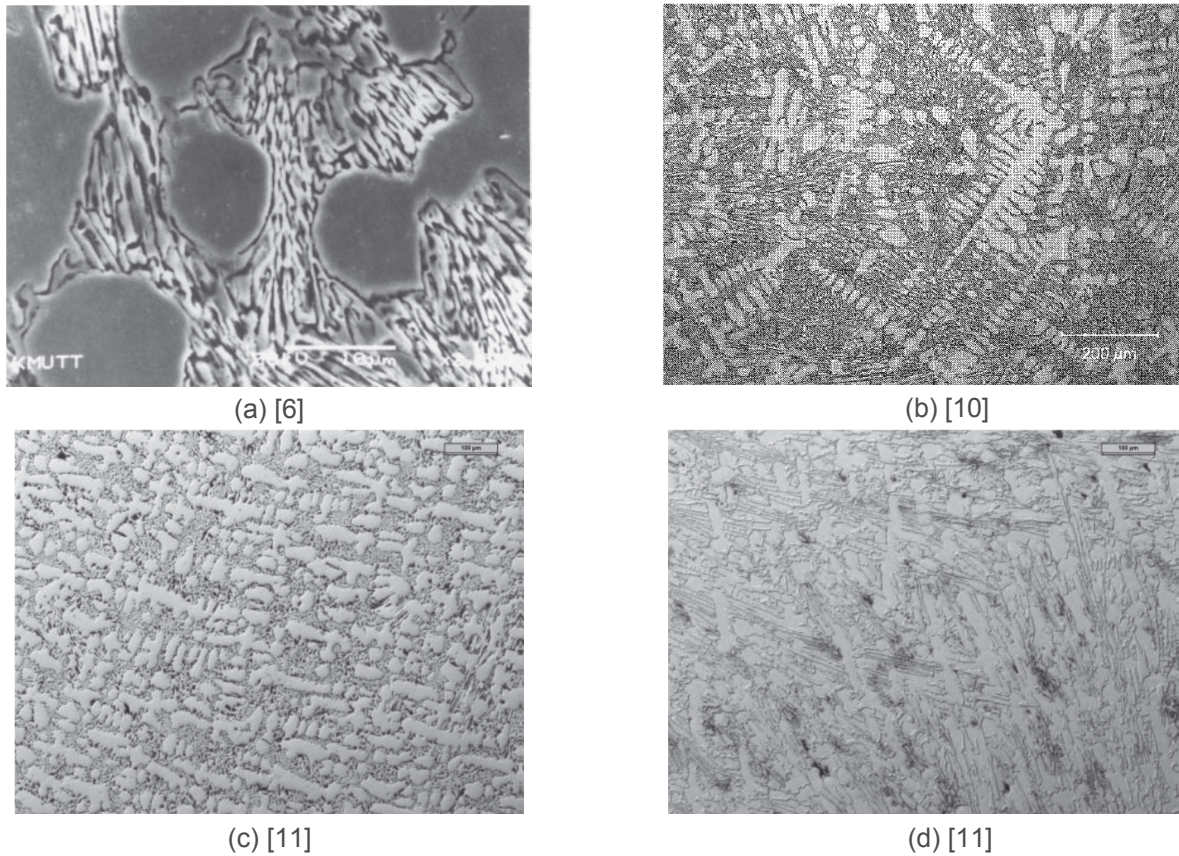
| (a) [6] | (b) [10] |
| (c) [11] | (d) [11] |

Figure 2 Typical micrographs of high chromium white cast iron

Heat treatment increases hardness of high chromium cast iron by destabilising the austenite and precipitation of Cr-rich secondary carbides generally at temperatures between 920°C and 1060°C for duration of up to 6 hours depending the extent of transformation required (usually 1 hour per 25mm of section thickness), followed by air cooling to room temperature during which austenite depleted of Cr and C transforms to martensite [12]. The ejected Cr and C then form secondary carbides in a martensite matrix with little residual austenite. Hardness increased to between 700 and 850 HV as a result of the destabilisation heat treatment. The destabilised structure consists of the network of eutectic carbides and secondary carbides precipitated in the prior austenite matrix which has been mostly transformed to martensite.

Tempering after quenching is often carried out at temperatures between 450 to 650°C, normally for up to 4 hours in order to reduce the amount of the retained austenite in the matrix and eliminate residual stress after quenching. Care must be taken to prevent transformation to pearlite and coarsening of secondary carbides [4] with prolonged tempering. A pearlitic structure may however be required for machinability of such castings. The pearlitic transformation occurs after sub-critical annealing at between 690 and 705°C for several hours after which hardness decreases to 400-450 HV. The hardness of the as-cast austenitic high Cr cast irons ranges between 500 and 520 HV. The British Cast Iron Research Association reports typical hardness of as-cast and annealed conditions is 400 HB with a mandatory minimum of 600 HB after heat treatment. Stabilised austenite in as-cast work hardens at the surfaces stained by deformation transforms to a wear-resistant martensitic structure on the surface in a similar way to the transformation that occurs in Hadfield steels.

3.   EXPERIMENTAL WORK

The experimental work was carried out in two parts. In the first phase of experiment, samples were sectioned from button samples of four selected heats A, B C and D in order to investigate the extent of variation arising

from short range segregation in thin sections, solidification occurs rapidly due to fast cooling. The melting and casting was closely monitored to reduce process variation and thus be able to assess effects of compositional differences. In the second phase, samples were cut from runners of castings from different heats in order to investigate the effects of long range segregation occurring during solidification of thick sections. Specimens were cut during normal production schedule at a foundry that produces castings for ore crushing in mineral processing. Sample E, F, G, H, I and J represent runner samples from different heats.

The metallurgical investigation was conducted at the Department of Metallurgy, University of Johannesburg. Chemical analysis of the cast iron was carried out using a Q4 Tasman spectrometer. Some samples were austenitised at 1050°C for 2 to 4 hours to allow saturation of austenite with C and Cr then rapidly quenched in oil followed by tempering at 500°C for 1 hour to 4 hours. As-cast and heat treated samples were sectioned, polished and etched in a mixture of ferric chloride and ethanol. Metallogaphic analysis was employed to evaluate the microstructural variation in as-cast as well as heat treated samples. Optical microscopy was carried out using the Olympus GX51 Inverted Microscope mounted with a camera for photomicrographs. The Scanning Electron Microscope (SEM) and the Energy Dispersive Spectroscopy (EDS) were employed for high resolution study of phases in the microstructure.

4. RESULTS AND DISCUSSION

4.1. Chemical composition

The internal specification used by the foundry shown in **Table 1** was fairly comparable to the BS4844: 1986 Grade 3D shown in **Table 2**, but with tighter control of elements with stipulated maximum limits. Carbon and chromium conform to Grade 3D. The deleterious elements such as sulphur and phosphorus were controlled to a maximum limit of 0.05% to improve the quality of castings. Keeping alloying elements e.g. Si (0.5-0.8%), Mn (0.6-1.0%), Ni (0.5%), Mo (1.5%) and Cu (0.5%) will have cost-saving implications. Manganese has the effect of refining the microstructure of the alloy and changes the carbide morphology and reduces size of carbides, perhaps because it contributes to stabilisation of austenite. Manganese also improves hardenability of cast iron and suppresses pearlite formation though lesser extent than Ni and Cu.

Despite the close control in chemical composition within the spectification, the mechanical properties were observed to be variable, more so in large castings. This probably indicates gross microstructural changes even with small differences in chemical composition or there were considerable variations in parameters of the production process such as pouring tempertature and size of casting. These in turn determine the solidification time.

Table 1 Chemical composition of selected samples and internal specification

Element	Internal Specification	Sample A	Sample B	Sample C	Sample D
C	2.0-2.8	2.722	2.528	2.681	2.645
Si	0.5-0.8	0.654	0.635	0.644	0.740
Mn	0.6-1.0	0.874	0.869	0.940	0.703
P	0.05 max	0.022	0.020	0.023	0.022
S	0.05 max	<0.100	<0.100	<0.100	<0.100
Cr	22.0-28.0	23.96	24.97	25.38	22.99
Ni	0.5 max	0.299	0.295	0.537	0.272
Mo	1.5 max	0.090	0.090	0.439	0.129
Cu	0.5 max	0.081	0.072	0.137	0.080
Fe	Balance	71.20	68.88	67.61	70.82

Table 2 BS4844: 1986 Grade 3D specification of high chromium cast iron

% C	% Cr	% Mo	% Mn	% Si	% Ni	% Cu	% S	% P
2.0-2.8	22-28	1.5 max	0.5-1.5	1.0 max	2.0 max	2.0 max	0.1 max	0.1 max

4.2. Microstructures

Figure 3 reveals somewhat little microstructural variation in the microstructures of button samples. The fact that some microstructural differences are observed in small button samples suggests that more pronounced variation in microstructures is expected in larger castings, where solidification time is much longer. The problem is exacerbated by when pouring temperatures are not standardized or controlled. Microstructural variation can be reduced to some extent by heat treatment, but gross segregation that occurs in large castings cannot eliminated entirely.
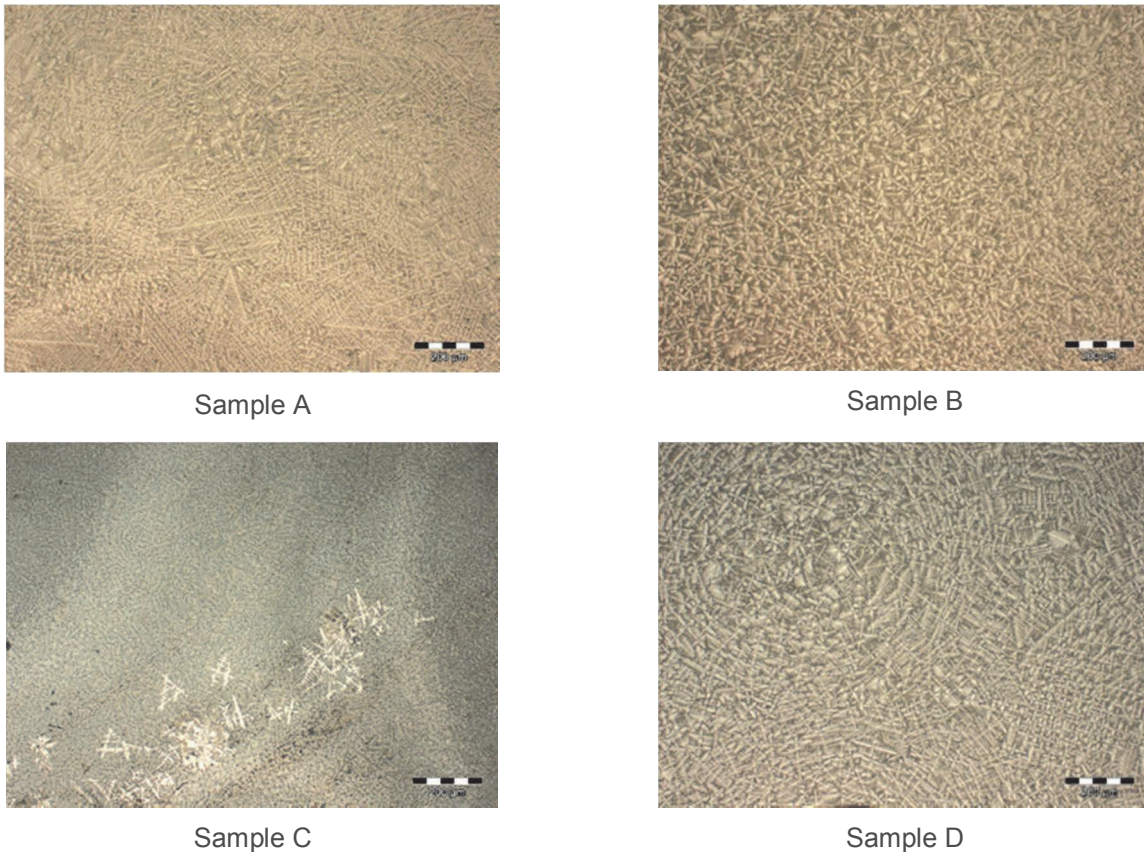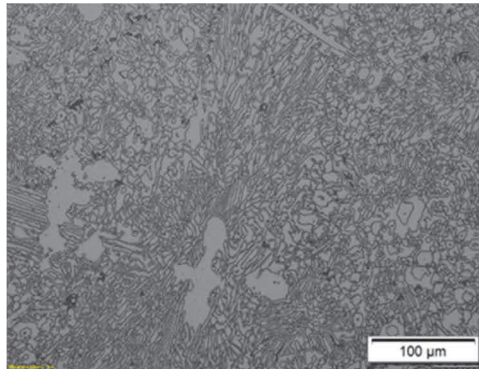

Sample A

Sample B

Sample C

Sample D

Figure 3 As-cast high Cr white cast iron micrographs from different heats

Figure 4 shows six micrographs from as-cast Samples E, F, G, H, I and J that were cut from runner samples of different heats. The microstructural variation increases in severity from Sample E to Sample H with Sample E being the best and most refined while Sample H is the worst. In Sample F primary austenite is coarser with increased volume fraction when compared with Sample E, indicating that the chemical composition of Sample F was further from eutectic composition than that of Sample E. Samples G and H show gross dendrites of primary austenite indicating significant growth of austenite during solidification. The elongated austenite in the eutectic matrix that is observed in Sample H shows needle-like appearance of the eutectic that is indicative of some directionality in solidifying front. Samples I and J have irregular microstructures where primary austenite and eutectic are not as clearly distinct. Such microstructures result from faceted and non-faceted eutectic growth mechanism where a faceted and non-faceted phases solidify competitively forming irregular eutectic

structures [5], The differences in microstructures in samples E, F, G and H demostrated that small shifts in chemical composition have considerable effects on the microstructures and also mechanical properties of high chromium white iron.

Controlling the chemistry of the alloy within a narrow range as well as strictly maintaining consistent pouring temperature reduces the microstructural variation. However, the cooling rate during solidification will always be dependent on the size of casting. In large sections cooling is much slower, resulting in long range segregation effects and variation in microstructures and mechanical properties.
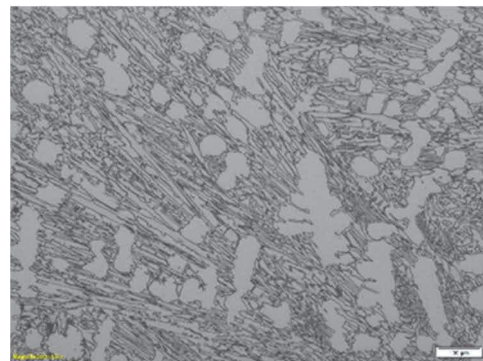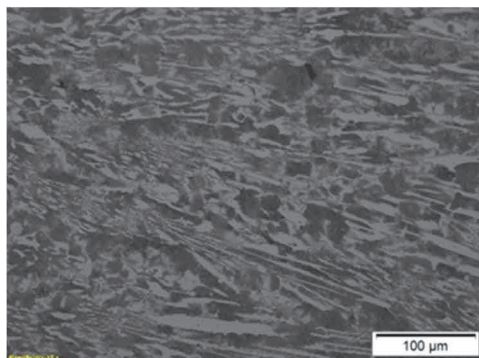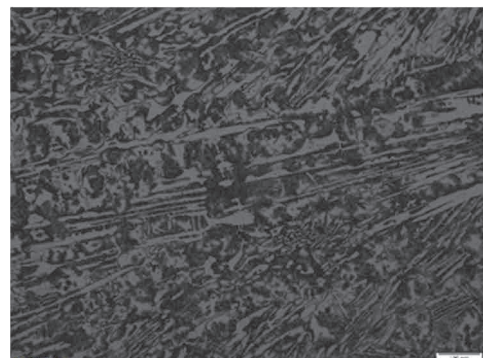

Sample E
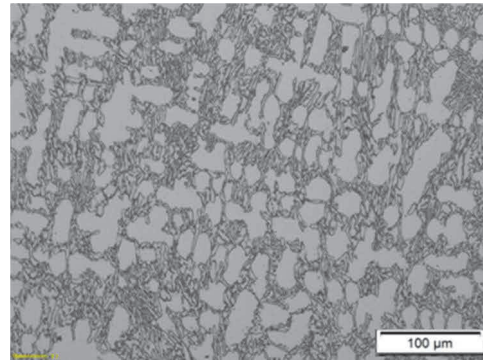
Sample F
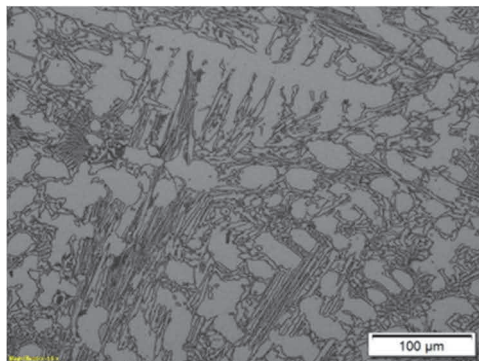
Sample G

Sample H

Sample I

Sample J

Figure 4 Microstructures of samples sectioned from runners

Despite the hardness values being well above the minimum specification of 400 BHN, there is a significant scatter in the hardness values of button sample conforming to the chemical specification. Elaborate variation

would be expected in runner samples and larger castings more so when the chemical specification is wide (in terms of carbon and chromium contents).

Basing on the general hardness profile of runner Samples E to J, it appears in that the more irregular the microstructure becomes (see **Figure 3**), the greater the degradation in mechanical properties. The hardness values of button samples in **Table 3** are significantly higher than those of runner samples shown in **Table 4**, which is due to the size effect of castings. It is expected that segregation and hence microstructural variation would be more severe in bulk castings than in runner samples due to much longer solidification times.

Table 3 Brinell hardness of as-cast high Cr white cast iron button samples

Trial runs	Sample A	Sample B	Sample C	Sample D
Test 1	587	507	592	555
Test 2	555	534	643	518
Test 2	601	547	627	564
Average	581	529	620	546

Specification 400 BHN minimum

Table 4 Brinell hardness of as-cast high Cr white cast iron runner samples

Trial runs	Sample E	Sample F	Sample G	Sample H	Sample I	Sample J
Test 1	514	510	435	471	467	472
Test 2	503	488	448	464	465	464
Test 2	507	503	441	471	473	466
Average	508	510	441	469	468	467

Specification 400 BHN minimum

The as-quenched hardness averaging 526 BHN was below the required minimum of 600 BHN and almost comparable to the hardness of as-cast samples. **Table 5** shows progressively increasing hardness from 1 hour temper to 2 hours, then decreased after tempering for 3 hours and 4 hours. This shows that prolonged tempering at 500ºC beyond 2 hours results in lower hardness and thus reduced wear resistance. Tempering temperatures other than 500ºC (within the recommended 450ºC to 650ºC) at varying times may have to be investigated.

Table 5 Brinell hardness of heat treated high Cr white cast iron runner samples

Trial runs	Austenitized at 1050 and tempered at 500 for 1 hour	Tempered at 500ºC for 2 hour	Tempered at 500ºC for 3 hour	Tempered at 500ºC for 4 hour
Test 1	522	637	616	582
Test 2	530	653	597	606
Test 2	526	648	582	569
Average	526	646	598	586

Specification 600 BHN minimum

5. CONCLUSION

The chemical specification of 2.0 - 2.8% C and 22-28% Cr stipulated for the BS4844: 1986 Grade 3D high chromium white cast iron proves to be too wide to achieve a consistent microstructure and maitain comparable

mechanical properties as required by customers. It is recommended that foundry practitioners adopt a narrower internal specification of 2.5 to 2.8% C and 25 to 28% Cr while maitaining a C:Cr of 1:10.5 in order to guarantee $(Cr,Fe)_7C_3$ carbide type in the eutectic. Process parameters such as pouring temperature and solidification time have a bearing in the final microstructure. High pouring temperature will invariably lead to long solidification time leading to unwanted grain growth. Furthermore, with slow cooling rates meta-stable austenite decomposes to ferrite and the undesirable type $(FeCr)_{23}C_3$ secondary carbides even at low Cr to C ratio. Controlling pouring temperature of 1550ºC is recomended. There will always be some variation in properties due to slow cooling caused by bulkiness of casting. This can be significantly reduced by narrowing the composition range and maitaining a consistent pouring temperature. For large castings, addition of 1.5% Mn is beneficial for refining austenite and suppressing the formation of pearlite. Chromite sand moulds are recommended for large castings to increase cooling rate and thus reduce solidification time. The optimum tempering time at a tempering temperature of 500ºC was found to be 2 hours beyond which hardness decreased.

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