An Overview on Types of White Cast Irons and High Chromium White Cast Irons

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Abstract
Crushing and grinding are widely used in mining, mineral processing, cement making, and coal power generation. The mechanical components that contact with materials being processed are working under the conditions of high abrasion and impact. How to reduce the wearing damages and prevent from the cracking failure of the mechanical parts is one of the crucial challenges facing the operations of many industries, involved crushing and grinding processes. Whit cast irons, and specifically high chromium white cast irons, have been developed and deployed worldwide for making mechanical components of crushing and grinding machines due to the combination of high wear resistance and good mechanical strength. The paper is aimed to give an overview on the white cast iron alloys, and particularly high chromium white cast iron alloys, including their classifications, their standard specifications in USA, China and Australia, their main usages and the new developments.

Keywords: white cast irons, high chromium white cast irons

1. Introduction
Many components in the mining and mineral industries are subjected to extreme conditions of abrasion and impact. The development of materials that offer improved resistance to abrasion and to withstand impact and fracture can lead to increased component life. This may then lead to substantial cost savings due to a reduction in base material costs, but perhaps more importantly, reduced downtime and maintenance costs, improved throughput and production. For mine operators, improvements in the abrasion resistance of, say the grinding balls in a ball mill, often not only a reduction in the amount of grinding media consumed, and hence greater throughput of ore [1], [2].

White cast irons, with content of chromium in particular, known as abrasion resistant cast irons, contain enough chromium to prevent continuous iron carbides (Fe₃C) or M₃C formation. Normally high chromium alloys would contain more than 10% Cr by mass. The iron will contain a significant percentage of carbon, which is essential for complex carbide formation, with other alloying elements that modify other mechanical properties and microstructures of the alloys [3] and [4]. HCWCI can be utilised not only as cast products, but also as hard-facing and coating materials [5]; [6]; [3] and [7].

The most important alloying elements are carbon (C) and chromium (Cr) present as carbides, which are mainly Fe₃C and Cr₇C₃. Complex carbides such as (Cr,Fe)₇C and (Cr,Fe)₂C₃, or MC, M₂C and etc. could also be present [4]. HCWCI are based on the iron-chromium-carbon (Fe-Cr-C) ternary system. These alloys consist of hard iron-chromium (Fe-Cr) carbide in a supportive matrix and
particularly suited for abrasion resistant applications [1]. White iron alloys in use today are highly alloyed materials, which require a sound understanding of the many metallurgical processes taking place in their production and processing. The high nominal concentration of chromium helps to prevent the formation of graphite and stabilise the carbide. Meanwhile, hardenability elements such as Mo, Mn, Cu or Ni, are typically added to suppress the formation of pearlite during cooling to room temperature [6]; [8]; [9]). In the mining industry, these alloys have been used in a range of situations that are subjected to varying conditions of impact and abrasive wear, such as crushing, screening and pumping as shown in Figure 1 [5]. In additions, white cast irons are used as sliding and rolling contacts such as chute liners, hoppers and feeder liner plates, screens, and work rolls for the hot rolling of materials, where they are required to process high resistance for sliding wear and rolling contact fatigue [5]. The wear resistance and mechanical properties of HCWCI depends on the type, morphology and distribution of carbides, volume fraction, and the nature of the supporting matrix structure which in turn depend on the chemical composition, the size of the cast wear part and on any subsequent thermal treatments [10].

2. Main usage of Cast Irons

The exceptional wear resistance of HCWCI results primarily from high volume fraction of hard Cr-rich carbides, although the toughness of the matrix also contributes to the wear resistance [9]. For abrasion resistance, nearly all HCWCI alloys used are hypoeutectic alloys containing 10 - 30 wt. %Cr and 2 - 3.5 wt. %C. High chromium irons in the compositional range of 12 - 30 wt. %Cr are extensively used for components that manipulate, mechanically process aggregates and raw materials (Figure 1). [11]. Such components include ore crushers (a) and (b), rollers (c), ball mill liners (d) and (e), and pulverising equipment (f) [5].

FIGURE 1. Illustrations of the cast wear-resistant components made from HCWCI alloys [11]

In wear applications that do not involve corrosion, for example, rollers and tables in coal pulverising or in dry ball mills, the most popular alloys are based on chromium levels of 18 - 22 wt. %Cr. In wet wear applications where combined abrasion and corrosion resistance is needed, for example slurry pumping (FIGURE 2) in extraction processes, grades containing 25 - 30 wt. %Cr are preferred [11]. The high chromium cast irons containing 30 - 40 wt. %Cr with lower carbon levels at 1.5 - 2.4 wt. %C have ferritic matrix structures. Ferrite (δ-Fe) is normally undesirable in abrasion-resistant high chromium cast irons since it is softer than austenite and does not work-harden significantly during wear service. However, there are ferritic chromium cast irons which have been developed for combined corrosion and abrasion resistance, and in particular for heat-resistant components [10]).
FIGURE 2. Slurry pumping components consisting of HGWCI alloys [11]

The microstructure of as-cast hypoeutectic composition of HGWCI alloy contains hard eutectic carbides of the form (Cr,Fe)7C3 supported in an austenitic matrix. The extent to which the matrix is fully austenitic depends on homogeneity and cooling rate. For example, localised carbon and chromium depletion during carbide formation can result in the transformation of austenite (γ-Fe) to martensite (α-Fe) at the eutectic carbide edges [12]. The hypoeutectic irons solidify as primary austenite dendrites with a network of interdendritic eutectic M7C3 carbides. Depending on the thickness and composition, notably Cr/C ratio and the levels of hardenability elements, the primary austenite may remain stable on cooling of the castings or it may fully or partially transform to pearlite [10].

Abrasion and corrosion resistance can normally be improved by destabilisation and tempering heat treatments. After air hardening, i.e. force air quench (FAQ) from destabilisation temperatures, the microstructure of a HGWCI consists of eutectic carbides, which are normally not affected by heat treatment, and precipitated secondary carbides in a martensitic matrix plus a small amount of retained austenite. Any retained austenite is transformed to martensite and/or bainite during subsequent tempering treatments. The type of secondary carbide formed during destabilisation depends on the composition and destabilisation temperature [10].

A vast effort has been devoted to the research of the Fe-Cr-C ternary system in an effort to establish all parameters of this system [4]. Although the high chromium white iron class of alloys covers both hypo- and hyper-eutectic alloys, this review will concentrate on the hypoeutectic grades commonly used as cast components. This review explores the relationship between the microstructure of high chromium white irons and the properties relevant to service in material applications (handling).

2.1. Cast Irons
Cast irons are ferrous alloys containing carbon contents generally between 2 and 4 wt. %. Ferrous alloys with carbon contents below 2 wt. % are called steels. The high amount of carbon in cast iron exceeds the solubility of this element in ferrite and/or austenite. The excess of carbon promotes the precipitation of a carbon rich phase during solidification, which remains during cooling to room temperature and this phase can be a carbide or graphite. Therefore, the final structure of cast irons is composed of a metallic matrix and carbide or graphite, depending on the chemical composition and on the solidification rate. According to the microstructure, cast irons are classified as white, gray, ductile and mottled irons [13] and [14].

Cast irons are heterogeneous alloys, which solidify with a eutectic phase. They contain Fe, C and Si as the major alloying elements and often incorporate Cr, Ni, Mn, Mo, Cu and other elements to enhance specific chemical and mechanical properties [14] and [15].

Cast iron structures are formed during crystallisation, cooling and heat treatment of these materials. During crystallisation process, the final type, content, distribution and geometry of cast iron phases are decided. On the other hand, the appearance of casting fracture depends on the type of high-carbon phases, i.e. graphite and cementite. Thus, conventionally, based on the appearance of cast iron fracture, grey and white cast irons, or mottled cast iron are distinguished, and on this division, the classification of cast iron grades correctly produced is based. The irons are referred to as “white” irons.
due to the appearance of the fracture surface of these irons compared to grey cast irons [11]; [3]; [16] and [4]. This work describes the abrasive wear-resistant white cast iron, in the structure of which there is a high content of carbides [14] and [17].

2.2. White Cast Irons

White cast iron is the only member of cast iron family in which carbon is present only as carbide. Because of the absence of graphite, it has a light appearance. The presence of different carbides makes white cast irons extremely hard and abrasion resistant, but very brittle. White cast irons are widely used in abrasive wear applications involved in the crushing, grinding, milling and handling of abrasive materials such as minerals and ores, both dry and as slurries. White cast iron can be divided in three classes [3]:

- Normal white cast iron – this iron contains C, Si, Mn, P and S, with no other alloying elements
- Low-alloy white cast iron – the total mass fraction of alloying elements is less than 5%
- High-alloy white cast iron – the total mass fraction of alloying elements is more than 5%

The three classes of white cast irons mentioned above have similar crystallisation rules and structures. The as-cast structures contains a large amount of carbides that make these irons very hard and brittle, and difficult to machine. These irons are wear resistant due to their high hardness and find wide applications for abrasion-resistant components [14]; [16] and [3].

ASTM specifications A532 covers the composition and hardness of white iron grades used for abrasion-resistance applications. Many castings are ordered according to these specifications; however, a large number of castings are produced with modifications to composition for specific applications [11] and [1]. The chemical compositions of several classes of white cast iron alloys are given in TABLE 1 and Class I are the Ni-Cr white cast irons, while Class II and III are HCWCI alloys.

**TABLE 1.** Composition (wt. %) of abrasion resistant irons according to ASTM A532-87 [3], [16] and [1]

| C. | T. | Des. | C    | Mn | Si | P   | S   | Cr | Mo | Ni | Cu |
|----|----|------|------|----|----|-----|-----|----|----|----|----|
| I  | A  | Ni-Cr-HC | 2.8 - 3.6 | 2  | 0.8 | 0.3 | 0.15 | 1.4 - 4.0 | 1  | 3.3 - 5.0 | -  |
|    | B  | Ni-Cr-LC | 2.4 - 3.0 | 2  | 0.8 | 0.3 | 0.15 | 1.4 - 4.0 | 1  | 3.0 - 5.0 | -  |
|    | C  | Ni-Cr-GB | 2.5 - 3.7 | 2  | 0.8 | 0.3 | 0.15 | 1.0 - 1.5 | 1  | 4   | -  |
|    | D  | Ni-HiCr  | 2.5 - 3.6 | 2  | 2   | 0.1 | 0.15 | 7.0 - 11  | 1.5| 4.5 - 7.0 | -  |
|    | A  | 12%Cr    | 2.0 - 3.3 | 2  | 1.5 | 0.1 | 0.06 | 11 - 14   | 3  | 3   | 1.2|
| II | B  | 15%Cr-Mo | 2.0 - 3.3 | 2  | 1.5 | 0.1 | 0.06 | 14 - 18   | 3  | 3   | 1.2|
|    | C  | 20%Cr-Mo | 2.0 - 3.3 | 2  | 1.0 - 2.2 | 0.1 | 0.06 | 18 - 23   | 3  | 3   | 1.2|
| III| A  | 25%Cr    | 2.3 - 3.3 | 2  | 1.5 | 0.1 | 0.06 | 23 - 30   | 3  | 3   | 1.2|

*Single values represent maximum alloy content, (LC) low carbon, (HC) high carbon, (HiCr) high chromium, (GB) graphite bearing, (C.) class, (T.) type and (Des.) designation.*

2.3. Normal white cast iron

Normal white cast iron is the oldest type of cast iron, produced especially for resistance against abrasion. It has been in production for centuries. This family of irons has many names, and foundrymen refers to these irons as pearlitic, indefinite chill iron, mottled white iron, chill iron, or simply white iron. In all cases, chilling the iron against a cold conductive surface and/or material forms the abrasion-resistant carbide network. Part of the carbon is in the form of graphite and another part is in the form of carbides. It is used in the production of items operating under conditions of dry friction (brake shoes) and wear-resistant parts, such as rollers, papermaking, and flour-milling shafts [11].
Normal white cast irons are unalloyed cast iron with low carbon and silicon content such that the structure is hard brittle iron carbide with no free graphite. These irons are limited in applications because of lack of impact resistance and the difficulty in maintaining the structure in thicker sections. In some cases, the castings are designed and produced to have a white structure in certain areas and a grey or flake structure elsewhere to improve toughness. Normal white cast iron, without any alloying elements, is used mainly in engineering for the following applications [4]:

- Abrasion resistant components without especially high wear-resistant casting requirements
- White cast iron for the manufacture of malleable castings

The composition characteristics for abrasion resistant components are high carbon and low silicon contents, so as to increase the amount of carbides to improve wear resistance. However, the chemical composition for white cast iron for making malleable iron castings contain higher silicon and lower carbon content, to accelerate graphitisation during the annealing process and improve the morphology of the resulted graphite [11]; [16] and [3].

The formation of carbides as opposed to graphite is brought by the ambivalent nature of the Fe-C system, where the carbon can be precipitated either as graphite (stable phase) or as Fe3C (metastable phase). The former results in the well-known family of grey iron, nodular, compacted graphite or malleable irons and the latter in low-alloy, abrasion-resistant irons or white irons. The metastable reaction in the Fe-C system occurs due to rapid cooling and typical requires that the liquid iron be solidified against a cold, conducting surface or “chill”. As the iron rapidly cools, it undergoes a eutectic solidification reaction, forming γ-Fe and Fe3C and/or α-Fe. Another name for this eutectic mixture of γ-Fe + Fe3C is ledeburite [11].

2.4. Low-alloy white cast iron

Low-alloy white cast iron occurs when alloying element(s) are deliberately added, but their total mass fraction is less than 5%. The functions of alloying elements are to increase the microhardness of carbides, strengthen the matrix and further improve wear. Alloying elements normally used include Cr, Ni, Mo, Cu, V, Ti and B. Normally, for low-alloy white cast iron, the silicon (Si) content is lower (general w(Si) = 0.4 - 1.2%) to ensure a “white” structure is obtained, in this case the range of carbon content is wider and is usually w(C) = 2.4 - 3.6%. Low-alloy white cast irons are used mainly for abrasion resistant castings [11].

There are different metallographic morphologies of eutectic cementite that can be observed in hypoeutectic low-alloy white cast irons, these are [18]): (1) Ledeburitic; (2) Network-like and (3) Plate-like.

The plate-like modification usually forms under large under-cooling conditions or high content P, Si, Te, Sb and Rare-Earth (RE) elements. Thus, the ledeburitic and net-work-like modifications are the ones most generally observed in morphologies of low-alloy white cast irons. Ledeburite and net-work-like modifications are produced in the form of massive and continuous carbides (playing the role of matrix) which could break up since dispersed particles would help in the tightening of these alloys [18].

2.5. High-alloy white cast iron

High alloy white cast irons have typical compositions of 15%Cr-3%Mo and 23 - 28 wt. %Cr and a superior combination of abrasion resistance and toughness. In some cases, they may be used as cast, but are normally hardened to develop the optimum properties. Some of these irons may also be machined after annealing and then hardened to produce a machined abrasion resistant part [11].

It is most desirable that the designer, metallurgist, and foundry worker cooperate to specify the composition, heat treatments, and foundry practice to develop the most suitable alloy and casting design for a specific application. According to the type of alloying elements used, high-alloyed white cast iron can be subdivided into three systems [19]; [16]; [3] and [11]:
The nickel-chromium (Ni-Cr) white cast irons
- The chromium-molybdenum (Cr-Mo) white cast irons
- The high chromium white cast irons (HCWCI)

2.6. Nickel-chromium (Ni-Cr) white cast irons
Nickel-chromium (Ni-Cr) irons are containing Ni and Cr. The Ni-Cr white cast irons, which are low-chromium alloy contains 3 - 5 wt. %Ni and 1 - 4 wt. %Cr, with one alloy modification which contains 7 - 11 wt. %Cr. The trade name Ni-Hard types 1 - 4 normally identify them. Chromium at lower concentrations (<2 - 3%), has little or no effect on hardenability, as most of chromium is tied up in the carbidates [16]and [11].

Ni-Cr white iron, the martensitic white cast irons and the martensitic Ni-Cr white cast irons are consumed in large tonnages in mining operations, such as ball mill liners and grinding balls [11]. Ni is the primary alloying element because at levels of 3.0 to 5.0%, it is effective in suppressing the transformation of the austenitic matrix to pearlite, thus ensuring that a hard martensitic structure (usually containing significant amounts of retained austenite) will develop upon cooling in the mould. Cr is included in these alloys, at levels from 1.4 - 4.0%, to ensure that the irons solidify carbide (M₇C₄-type), that is, to counteract the graphitisation effect on Ni [20].

Abrasion resistant structures containing eutectic mixtures of austenite and carbides can be obtained in thin and thick section sizes independent of the use of chill. It is possible to obtain traces of graphite in thicker sections or when higher levels of carbon and silicon are employed. Barring these circumstances, the dominant microstructure of Ni-Hard iron is one composed of a ferrous matrix surrounded by hard metal carbides [11].

The presence of 3 - 5 wt. %Ni allows proeutectic austenite to reach the martensite start (Mₛ) temperature unhindered by the transformation of pearlite. No transformation is perfect and as-cast Ni-Hard iron microstructure will contain a mixture of austenite and martensite. If the casting is of variable thickness, then thicker sections might contain traces of pearlite. From this discussion, it is obvious that it is quite difficult to make predictions about the wear performance of the casting, which is based on initial chemistry, with little or no knowledge about dimension or thermal history [11].

For applications requiring a high degree of strength, hardness and wear resistance, Ni-Hard cast irons are among the effective material available. Ni-Hard iron castings have shown outstanding in variety of severe applications including work rolls for hot steel milling. High chromium cast irons and high-speed steel type alloy are also widely used in steel plant, and Ni-Hard iron is generally used in finishing stands [20]. The optimum composition of Ni-Cr white cast iron alloy depends on the mechanical properties required for the service conditions and the dimensions and weight of the casting. The Ni-Cr white cast irons have proven to be very cost effective materials that are used for crushing and grinding.

The predominant characteristics of Ni-Hard irons are that their high strength and toughness can be achieved when heat-treated at relatively low temperatures. Low temperatures for heat treatment are favourable for large castings that are not suitable for heat treatment at higher temperatures and are prone to cracking [11]; [16]. Of all the abrasion resistant irons, Ni-Hard is produced in the largest tonnage for a variety of mineral processing industries. Ni-Hard iron’s low costs is due to its low alloy content, its ability to be cast into a variety of shapes and its high hardness in the as-cast condition. Its high hardness is what clearly separates it from pearlitic abrasion resistant cast iron. High hardness results from the formation of martensite versus pearlite in the as-cast condition. This metallurgical shift is the result of Ni-Hard iron’s high Ni content [11].

In Class I Type A, the castings in applications require maximum abrasion resistance, such as ash-pipes, slurry pumps, roll heads, muller tires, coke crusher segments, classifiers etc. Type B is recommended for applications requiring more strength and exerting moderate impacts, such as crusher plates, crusher concaves, and pulverising pegs. Class I Type D, Ni-Hard Type 4, has a higher level of strength and toughness and is therefore used for the more severe applications that justify its added
alloy costs. It is commonly used for pumps volutes handling abrasive slurries and coal pulveriser table segment and tires.

The Class I Type C alloy (Ni-Hard 3) is specially designed for the production of grinding balls. This grade is both sand cast and chill cast, chill casting has the advantage of lower alloy cost, more important, provides a 15 - 30% improvement for 8hrs at 260 - 315°C [11]. There are two general types containing 4%Ni-2%Cr, and 6%Ni-8%Cr. Both have a structure of iron and chromium-carbides in a matrix of martensite and bainite, but the higher alloy content materials have a type of carbide that is discontinuous and confers greater impact and corrosion resistance, i.e. M7C3 type of carbide. These irons can be used as cast, but heat treatment improves the hardness and resistance to surface cracking and spalling.

2.7. Chromium-molybdenum (Cr-Mo) white cast irons
These irons are for abrasion resistance application and the chromium-molybdenum (Cr-Mo) irons (Class II of ASTM A532) contain 11 - 23 wt. %Cr, up to 3 wt. %Mo and are often alloyed with Ni or Cu. They can be supplied either as cast with an austenitic or austenitic-martensitic matrix, or heat-treated with a martensitic microstructure for maximum abrasion resistance and toughness [12].

They are usually considered the hardest of all grades of white cast iron. Compared to the lower-alloy Ni-Cr white irons, the eutectic carbides are harder and can be heat treated to achieve castings of higher hardness. Mo, as well as Ni and Cu when needed, is added to prevent pearlite and to ensure maximum hardness [11].

High chromium white cast irons (HCWCI)
Wear is a significant problem faced in many industries, and replacement of worn parts can result in considerable costs arising from the cost of the replacement components, labour and loss of production time, and reduced productivity from capital equipment. To minimise these costs and attendant downtime of equipment, wear resistant materials are commonly used in high wear environment. One of the most commonly used groups of materials for wear resistance is high chromium white cast irons (HCWCI) alloys [21]; [11].

HCWCI undergo several solidification reactions and a number of different solid-state transformation reactions on cooling to room temperature, during reheating to elevated temperature below solidus temperatures. Consequently, a number of different phases form in HCWCI that influences the mechanical properties and service life of the material [21]; [19].

The irons under this heading have the highest Cr-content within the high-alloy white cast iron family. High Cr gives these irons good wear resistance, corrosion resistance, impact toughness and hardenability [22], [23]. The resistance to corrosion and abrasive wear, and wear at elevated temperature are also remarkably improved [16]. Class I and II of high chromium white irons are superior in abrasion resistance and are used effectively in impellers (a) and volutes (b), impeller blades (c) and liners (d) for short blasting equipment, and refiner disks (e) in pulp refiners [16].

2.7.1. Chinese Standard
There are mainly four types of Cr-Mo high-alloy white cast irons in the Chinese National Standard and the chemical compositions are given in table.
Among these, the medium chromium white cast iron (KmTBCr8) is the wear resistant material with Chinese characteristics, especially the high silicon to carbon (Si/C) ratio. Medium chromium white cast iron and medium chromium-silicon white cast iron (both belong to KmTBCr8) have been widely used in China. The main features of these irons are the alloying of carbon and chromium to give a ratio of Cr/C ≈ 3, and the formed eutectic carbide is of the type M7C3, thus giving the irons excellent combination of properties and higher performance/price ratio [16].

The KmTBCr12 has limited hardenability, so it is not normally heat-treated, except for stress relief. The as-cast matrix structure is pearlite (which has good impact fatigue strength) and M7C3 eutectic
carbides. KmTBCr15Mo is a type of high chromium white cast iron, which has been studied deeply and is widely used. It is normally air quenched and tempered and has high hardness, strength and toughness, with excellent resistance to corrosion and impact-abrasion. KmTBCr20Mo iron has high chromium content and thus a higher Cr/C ratio; hence, it has better hardenability, hardness, toughness, and corrosion resistance. This iron is suitable for thick section components used under certain impact and wet abrasion-wear conditions [16].

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![Image of typical cast components](image_url)

**FIGURE 3.** High chromium cast irons typical cast components [11]

**TABLE 2.** Specification and composition of Chinese abrasion resistant white irons (GB/T8263-1999) [3] and [11]

| Specification (1) | Chemical composition (wt.) |
|------------------|----------------------------|
|                  | C  | Si | Mn | Cr  | Mo | Ni | Cu |
| KmTBNi4Cr2-2     | 2.4 - 3.0 | ≤ 0.8 | ≤ 2.0 | 1.5 - 3.0 | ≤ 1.0 | 3.3 - 5.0 | - |
| KmTBNi4Cr2-3     | 3.0 - 3.6 | ≤ 0.8 | ≤ 2.0 | 1.5 - 3.0 | ≤ 1.0 | 3.3 - 3.0 | - |
| KmTBCr9Ni5       | 2.5 - 3.6 | ≤ 2.0 | ≤ 2.0 | 7-11 | ≤ 1.0 | 4.5 - 7.0 | - |
| KmTBCr2          | 2.1 - 3.6 | ≤ 1.2 | ≤ 2.0 | 1.5 - 3.0 | ≤ 1.0 | 1.0 - 1.2 | - |
| KmTBCr8          | 2.1 - 3.2 | 1.5 - 2.2 | ≤ 2.0 | 7-11 | ≤ 1.5 | 1.0 - 1.2 | - |
| KmTBCr12         | 2.0 - 3.3 | ≤ 1.5 | ≤ 2.0 | 11-14 | ≤ 3.0 | 2.5 - 1.2 | - |
| KmTBCr15Mo(2)    | 2.0 - 3.3 | ≤ 1.2 | ≤ 2.0 | 14 - 18 | ≤ 3.0 | 2.5 - 1.2 | - |
| KmTBCr20Mo(2)    | 2.0 - 3.3 | ≤ 1.2 | ≤ 2.0 | 18 - 23 | ≤ 3.0 | 2.5 - 1.2 | - |
| KmTBCr26         | 2.0 - 3.3 | ≤ 1.2 | ≤ 2.0 | 23 - 30 | ≤ 3.0 | 2.5 - 2.0 | - |
Note: Ni-Hard irons: (S) ≤ 0.15 wt. %, (P) ≤ 0.15 wt. %; KmTBCr2: (S) ≤ 0.1 wt. %, (P) ≤ 0.15 wt. %. All other specifications: (S) ≤ 0.06 wt. %, (P) ≤ 0.10 wt. %.

2.7.2. ASTM Standard

The high chromium irons (Class III of ASTM A532), are generally purposed irons, also called 25%Cr irons, containing 23 - 28%Cr with up to 1.5%Mo. To prevent pearlite and attain maximum hardness, Mo is added in all but the lightest-cast sections. Alloying with Ni and Cu up to 1% is also practical. Although the maximum attainable hardness is not as high as in the Class II Cr-Mo white irons, these alloys are selected when resistance to corrosion is desired. In many applications, they withstand heavy-impact loading, such as from impact hammers, roller segments and ring segments in coal grinding mills, feed-end lifter bars and mill liners in ball mills for hard-rock mining, pulveriser rolls, and rolling mill rolls [16].

In an acidic medium white cast iron with w(Cr) = 28% has much better wear resistance and high temperature oxidation resistance than a white cast iron with w(Cr) = 15%. The C-content of this white cast iron can vary between w(C) = 2.0 - 3.3%, increasing the Cr-content and reducing the C-content can improve its corrosion and abrasion resistance. Cr26 HCWCI castings are used mainly after quenching and tempering, but can also be used as-cast [16]and [10]. Irons for corrosion resistance are alloys with improved resistance to corrosion, for applications such as pumps for handling fly ash, are produced with higher Cr-content (26 - 28%) and low C-content (1.6 - 2%). These irons provide the maximum Cr-content in the matrix. The addition of 2 wt. %Mo is recommended for improving resistance to chloride containing environment. Full austenitic matrix structures provide the best resistance to corrosion, but some reduction in abrasion resistance must be expected. Castings are normally supplied in the as-cast conditions [16].

Because of castability and cost, HCWCI castings can often be used for complex and intricate parts in high-temperature applications at considerable savings compared to stainless steel. These cast irons grades are alloyed with 12 - 39 wt. %Cr at temperatures up to 1040°C for scaling resistance. Cr causes the formation of an adherent, complex, Cr-rich oxide film at high temperatures. The high Cr irons designated for use at elevated temperatures fall into one of three categories, depending on the matrix structures [16]:

- Martensitic irons alloyed with 12 - 28 wt. %Cr
- Ferritic irons alloyed with 30 - 34 wt. %Cr
- Austenitic irons that contain 15 - 30 wt. %Cr as well as 10 - 15 wt. %Ni to stabilise the austenite phase

The C-content of these alloys ranges from 1 - 2%. The choice of an exact composition is critical to the prevention of sigma-phase (σ-Fe) formation at intermediate temperatures and at the same time avoids the ferrite-to-austenite transformation during thermal cycling, which leads to distortion and cracking. Typical applications include recuperator tubes, breaker bars and trays in sinter furnaces, grates, burner nozzles, and other furnace parts, glass moulds and valves seats for combustion engines [16].

2.7.3. Australian Standard

An Australian Standard, AS 2027:2007; has adopted the ISO 21988:2006 classification of HCWCI and covers five grades ranging in chromium contents from 11 - 40 wt. %. The designation and chemical composition of HCWCI are given in TABLE. Other international standards such as ASTM A532/A 532M-93a;1999 have similar designations with respect to the Cr-composition range but differ in the minimum and maximum amount of addition alloying elements.
Table 3. shows the different designation of high Cr abrasion resistant cast irons cross-referenced with other international standard [24].

The most notable difference between the AS 2027:2007 (adopted from ISO 21988:2006) together with the previous superseded AS 2027:2002 standard is the inclusion of ISO 21988/ JN/HBW600XCr35 or Cr35 designation. This particular designation refers to a HWCWI having Cr and C-content in the range of 30 - 40 wt. %Cr and 3 - 5.5 wt. %C, respectively. The Cr and C-contents are well above what is specified in other standards (e.g. ASTM A532:1999) [24].

TABLE 3. Brinell hardness and chemical composition of HWCWI (AS 2027:2007) [11] and [24]

| M.D.S.                  | BHN | Chemical composition (wt. %) |
|------------------------|-----|------------------------------|
|                        |     | C   | S   | Mn | P  | S   | Cr  | N   | Mo | Cu |
| ISO21988/JN/HBW555XCr13| 555 | 1.8-3.6 | 1   | 0.5 | 1.5 | 0.08 | 0.08 | 7-14 | 2  | 3  | 1.2 |
| ISO21988/JN/HBW555XCr16| 555 | 1.8 | 1   | 0.5 | 1.5 | 0.08 | 0.08 | 14-  | 2  | 3  | 1.2 |
| ISO21988/JN/HBW555XCr21| 555 | 1.8 | 1   | 0.5 | 1.5 | 0.08 | 0.08 | 18-  | 2  | 3  | 1.2 |
| ISO21988/JN/HBW555XCr27| 555 | 1.8 | 1   | 0.5 | 1.5 | 0.08 | 0.08 | 23-  | 2  | 3  | 1.2 |
| ISO21988/JN/HBW600XCr20| 600 | 3.6 | 1   | 1   | 1.0 | 0.08 | 0.08 | 30-  | 1  | 1.5 | 1.2 |
| ISO21988/JN/HBW600XCr20MoCu| 600 | 2.6-2.9 | 1 | 1   | 0.06 | 0.06 | 18-  | 1  | 1.4 | 0.8 | 1.2 |

(M.D.S.) Material designation symbol; (BHN) Brinell hardness number (minimum value) and Single values represent maximum alloy content

Table 4. HWCWI cross referenced with other international standards [11]and [24]

| ISO21988:2006/AS2027-2007 | AS2027-2002 | EN12513:2001 | ASTM:1999 | DIN1695:1981 |
|---------------------------|-------------|--------------|-----------|---------------|
| ISO21988/JN/HBW555XCr13   | EN-GJNHV (XCr11) | 600          | 12%Cr     | G-X 300CrMo   |
| -                         | –           | –            | –         | 15 3          |
| ISO21988/JN/HBW555XCr16   | CrMo15 3    | EN-GJNHV (XCr14) | 600      | G-X 300CrMoNi |
| –                         | –           | –            | –         | 15 2 1        |
| ISO21988/JN/HBW555XCr21   | CrMo 20 1   | EN-GJNHV (XCr18) | 600      | G-X 260CrMoNi |
| –                         | –           | –            | –         | 20 2 1        |
| ISO21988/JN/HBW600XCr20MoCu| CrMoCu20 2 1 | –            | –         | –             |
| ISO21988/JN/HBW555XCr27   | Cr27Lc and Cr27 Hc | EN-GJNHV (XCr23) | 600    | G-X 260Cr27   |
| –                         | –           | –            | –         | –             |
| ISO21988/JN/HBW600XCr35   | Cr 35       | –            | –         | –             |
Based on the ratio of carbon versus added alloying elements, high chromium cast irons could present hypoeutectic, eutectic and hypereutectic compositions [24]. The structures of Cr-carbides are largely dependent on the composition of the high chromium irons. The range of composition of high chromium irons means that there are three possible categories that the resulting solidification paths. These solidification paths can lead to hypoeutectic, eutectic or hypereutectic microstructures [19].

These three classes of high chromium irons microstructures have similar crystallization rules and structures. The as-cast structure contains large amounts of Cr-rich carbides, ((Cr,Fe)7C3 or M7C3, where M is a metal, such Cr or Fe) that makes irons very hard and brittle, and difficult to machine [11]; and [25].

Among the metal alloys of high wear-resistance and strength, besides white cast iron alloys, high manganese steel is another alloy used widely in the processes of crushing and grinding [26], due to the excellent combination, caused by its unique property of “working hardness” [27], of high wear-resistance and high mechanical strength, [28].

3. Conclusion

White cast iron alloys and high chromium white cast iron alloys in particular are overviewed in this paper. White cast irons include normal white cast irons, low alloy white cast irons, high alloy white cast irons, nickel-chromium white cast irons, chromium-molybdenum white cast irons, and high chromium white cast irons with Chinese standard, ASTM standard and Australian Standard.

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