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# Dry Sliding Wear Behaviours of Valve Seat Inserts Produced from High Chromium White Iron

**Abstract:** In this present study, wear behaviours of high chromium white iron valve seat inserts and tappets used in the automotive sector were investigated. Wear behaviours of three different rates of high chromium white cast irons (containing 10, 12 and 14% chromium) were examined under heavy service conditions. For that purpose, the produced valve seat inserts were characterized through Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS), X-ray diffraction (XRD) and hardness measurements. They were tested at a sliding speed of 1 $ms^{-1}$, under 120 N load and for six different sliding distances (500, 1000, 1500, 2000, 2500, 3000 m) by using a standard wear apparatus (pin-on-disk type). The result showed that as the amount of Cr increased in the alloys, their hardness decreased. The decrease in the hardness were considered to be as the result of transformation of $M_7C_3$ carbides into $M_{23}C_6$ carbides in the structure. This decrease in hardness with increasing chromium content also increased the weight loss. Thus, it was determined that the white iron with 14% Cr (which had a greater amount of $M_{23}C_6$ carbides) was subjected to the highest wear.

**Keywords:** valve seat insert, wear behaviour, Cr rate, high chromium white cast iron

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## 1 Introduction

Valve and valve seat insert producers constantly work with engine producers in an attempt to increase the ser vice life of valves and valve seat inserts. Progresses being made in the production and design of valve seat inserts have substantially increased the durability and performance of engines [1]. Valve seat inserts are equipments facilitating a contact surface for the tappet when it is closed. A full contact is provided between the contacts surfaces of tappet-valve seat insert as the engine cylinders function, which prevents the loss of pressure by providing impermeability in the combustion chamber. Thus, the wear observed on valve seat inserts negatively affects the engine performance [2]. Valve and engine producers commonly aim to increase the valve quality and life and consequently develop the performance of the engines. Tappets and valve seat inserts are the components that function under heavy conditions in engines. As they constantly operate under high pressure and high temperature, the exhaust tappets are expected to function without any decomposition. Thus, both tappets and valve seat inserts are required to have a high strength against fracture, corrosion and especially wear. In order to enable these components to precisely function, they are made of hard metals and alloys that are hardened with heat treatment. These components are generally produced using special-alloyed steels with a high thermal and wear resistance. As the valve seat inserts that are produced from specially alloyed steels function under heavy conditions in engines, they are required to be cooled in order to avoid decomposition and wear. Unless the appropriate conditions are provided for the cooling process, they lose their mechanical strength, rapidly worn and lose their function of impermeability.

Valve seat inserts are produced using different production methods. These components could be produced with both the powder metallurgy and the casting methods [3]. The greatest problem encountered in powder metallurgy productions is the failure of attaining the full density in components being produced. Besides, the need for additional processes to attain the full density (100%) also increases the production costs. Thus, the method mostly preferred in the production of valve seat inserts is the casting method. As the valve seat inserts that are produced with the casting method function under heavy conditions in engines, a wear-type damage is observed in these components. In order to decrease the wear, these components are produced from high chromium white iron. These materials are used in the production of machine elements (such as slurry pumps, grinder and crusher elements and cement pipes) that are required to have a high wear and corrosion resistance [4–7]. It is known that the chromium carbide that is formed in the structure of the high chromium white iron during the casting process increases the mechanical properties and wear resistance of the material [8]. Following the casting, the microstructure is formed of austenite and $M_7C_3$ carbides [9]. Wear resistance generally depends on structural properties such as the microstructure of matrix, as well as the types, size, morphology, distribution and orientation of carbide. In addition to this, the volume rate, fracture toughness and alloy hardness of carbides that are formed in the structure also affect the wear resistance. Environmental factors such as the load conditions affecting the material, tribological environmental features, motion on the contact surface, as well as the size and type of abrasive surfaces also affect the wear of this material [10].

The most important phase delaying the wear in the structure of high chromium white iron is hard $M_7C_3$ carbides that are formed in the structure during solidification of the alloy. When wear occurs in the matrix, fractures are observed in hard carbides exposed to stress. In some conditions, the fractured carbides are embedded within the soft matrix and form a hard surface layer [8]. Serious wear problems are encountered in valve seat inserts due to the high performance expected from engines and the increasing use of alternative fuels (such as LPG). Three types of mechanical damages occur in valve seat inserts during their service. These are adhesive wear, abrasive wear and plastic deformation caused by thermal factors [11–13]. Valve seat inserts are produced from alloy steels involving high amounts of Cr, Ni, Si and some other elements, as well as specially-alloyed steels called stellite, which are resistant to high temperature. In recent years, instead of high cost specially-alloyed steels, high chromium white iron materials that have similar properties have been used in the production of valve seat inserts. Thus, the present study aims to examine the influence of chromium content on wear behaviour of high chromium whit iron engine valve seats under heavy performance conditions. Three different chromium amounts (10, 12 and 14%) were used and its effect on the microstructure was also investigated.

## 2 Material and method

For the experimental studies, AFS 80–100 quartz sand and UNIFENB18 resin (at a volume of 2.5%) were used in the preparation of moulds and $CO_2$ gas as the hardener. Resin was added into the dry sand and it was mixed within a mixer for 5 minutes at a speed of 45 rpm. After the completion of the process of sand preparation, it was compressed within a canister at a pressure of approximately 7 bars. Following this process, the moulds were hardened by flowing $CO_2$ gas through the mould for 2 seconds per 1 kg resin sand. After the preparation of moulds, the high chromium white iron alloys whose chemical compositions are given in Table 1 were melted and poured.

Melting processes were performed on an induction furnace with a melting capacity of 300 kg. Following the melting process, the slug was removed by refining the liquid metal. The liquid metal was transferred from the melting furnace to ladles and then poured in the moulds. The process of pouring from the ladle to the mould was performed at approximately 1923 K. Figure 1 shows the image of the prepared mould, the casting components, valve insert and representative of specimen removed from valve seat insert.

For the characterization studies, samples of 6.5 mm diameter were prepared from valve seat inserts containing three different amounts of Cr on an EDM die sinker. Following the standard metallographic processes, all the samples were etched with 1 g $FeCl_3$, 2 ml $HNO_3$, 0.6 ml HCl and 17 ml ethanol solution for 150 min [14]. The etched samples were characterized through scanning electron microscopy (SEM+EDS/JEOL 6060), X-ray diffraction (XRD/Rigaku), density measurements (Archimets) and hardness measurements (AffriSystem VRSD-251/HV2). The hardness values were obtained by calculating the mean

**Table 1:** Chemical compositions of valve seat inserts

| | C | Si | Mn | Cr | Mo | Ni | Nb | Cu | Ti | V | W | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| %10 Cr | 2.184 | 1.274 | 0.783 | 9.955 | 0.242 | 0.242 | 0.023 | 0.684 | 0.012 | 0.269 | 0.056 | Balance |
| %12 Cr | 2.367 | 1.402 | 0.776 | 11.992 | 1.291 | 0.237 | 0.028 | 0.682 | 0.018 | 0.260 | 0.050 | Balance |
| %14 Cr | 2.215 | 1.408 | 0.732 | 14.021 | 1.243 | 0.236 | 0.032 | 0.704 | 0.020 | 0.261 | 0.055 | Balance |

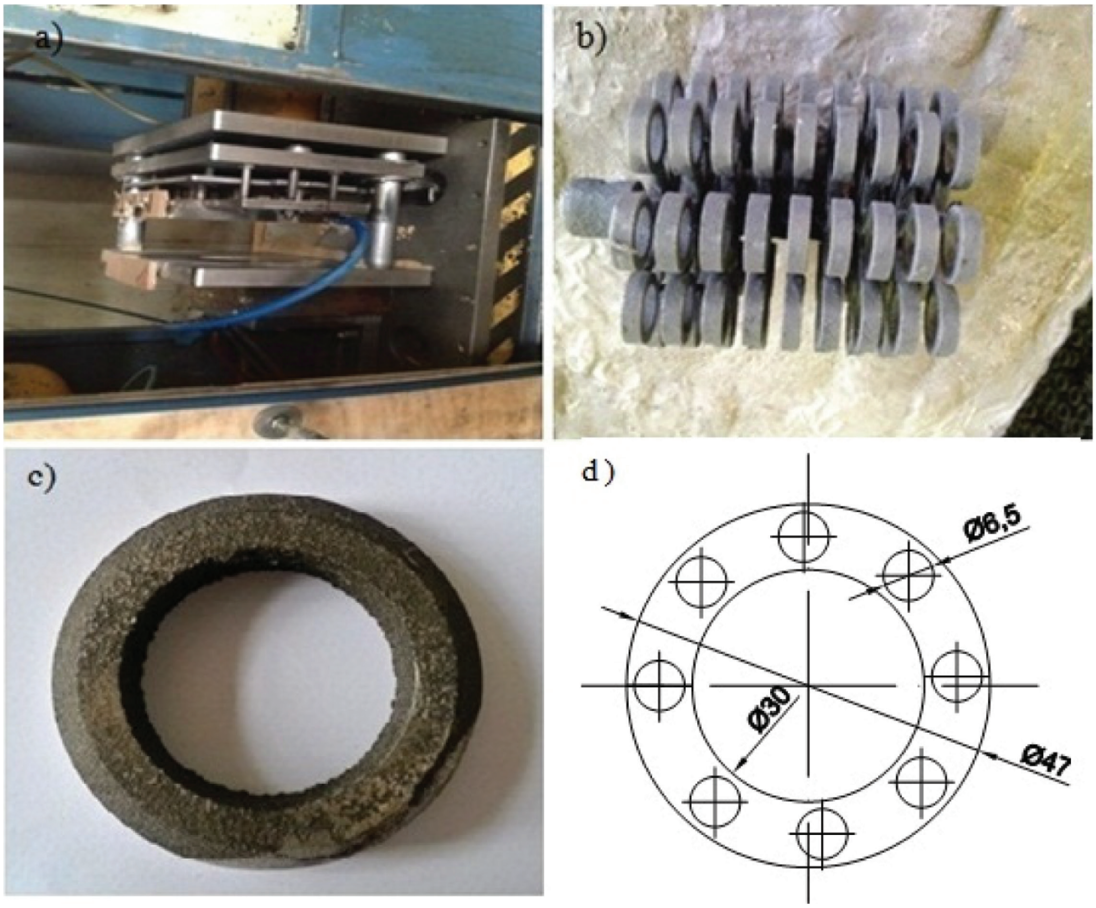


**Fig. 1:** (a) Prepared mould, (b) moulded parts, (c) valve seat insert, (d) representative of specimen removed from valve seat insert

of approximately 5 hardness measurements from each sample. The density was measured by taking 5 samples from each alloy group according to the principle of Archimeds.

A pin-on-disk-type standard test apparatus was used forwear tests. This apparatus could be able to function at every load, sliding speed and different cycles. Before the wear tests, the samples' surfaces were polished with a 1200 grid sandpaper and using a 6 µm diamond paste. By this way, the same surface quality was provided for each sample. During the wear tests, the samples were tested at 120 N constant load, 6 different sliding distances (500–3000 m) and 1 $ms^{-1}$ sliding speed. Surfaces of abrasive discs and samples were cleaned with acetone before the wear tests. The worn samples were measured on a 1/10000-sensitive scale and their weight losses were determined. The material of counter discs for wear tests was the same as that of the samples to be worn. The formula used in calculation of the wear rate is given in Eq. (1).

$$Wa = \frac{\Delta G\ (mg)}{d \cdot P \cdot S\ (g/cm^3 \cdot N \cdot m)} \tag{1}$$

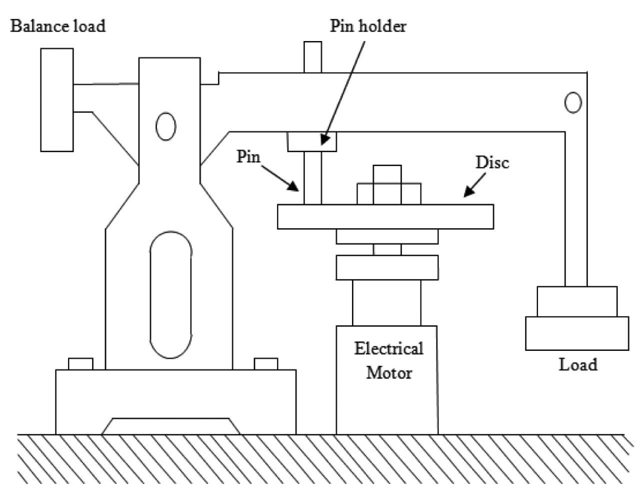


**Fig. 2:** Schematic display of the pin-on-disk-type standard wear apparatus

where Wa = signifies the wear rate ($mm^3$/Nm), ΔG = weight loss (mg), P = loading weight (N), S = sliding distance (m) and d = density ($g/cm^3$). Besides, the worn surfaces of samples were also examined with SEM. Figure 2 schematically shows the pin-on-disk-type standard wear apparatus.

# 3 Results and discussions

## 3.1 Microstructural examinations

Figure 3 shows the SEM images of the microstructures obtained from the as-cast high chromium white iron containing Cr at different rates (10%, 12% and 14%). The SEM images in Figure 3 show that the microstructure of as-cast samplecomprises austenitic dendrites, as well as eutectics and carbides in the grain structure of matrix. Besides, an austenite-martensite transformation (caused by regional depletion of Cr and C) is observed in the structure. According to the SEM images given in Figure 3, it is observed that coaxial grain structure is dominant in the matrix of the alloys containing 10% and 14% Cr, whereas the SEM image of the alloy containing 12% Cr shows that the grains are columnar.

The results of the EDS analysis of 10% Cr specimen given in Table 2, it is seen that the Cr rate is 51% in the light-colored areas. Besides, the areas seen as small fractures within the matrix are thought to be oxide film layers.

## 3.2 XRD results

The result of the XRD analysis is given in Figure 4, which was performed to determine the phases within the material. When the XRD analysis result of the sample containing 10% Cr is examined, it is seen that the peak values given by $M_7C_3$ and $M_{23}C_6$ carbides within the structure are

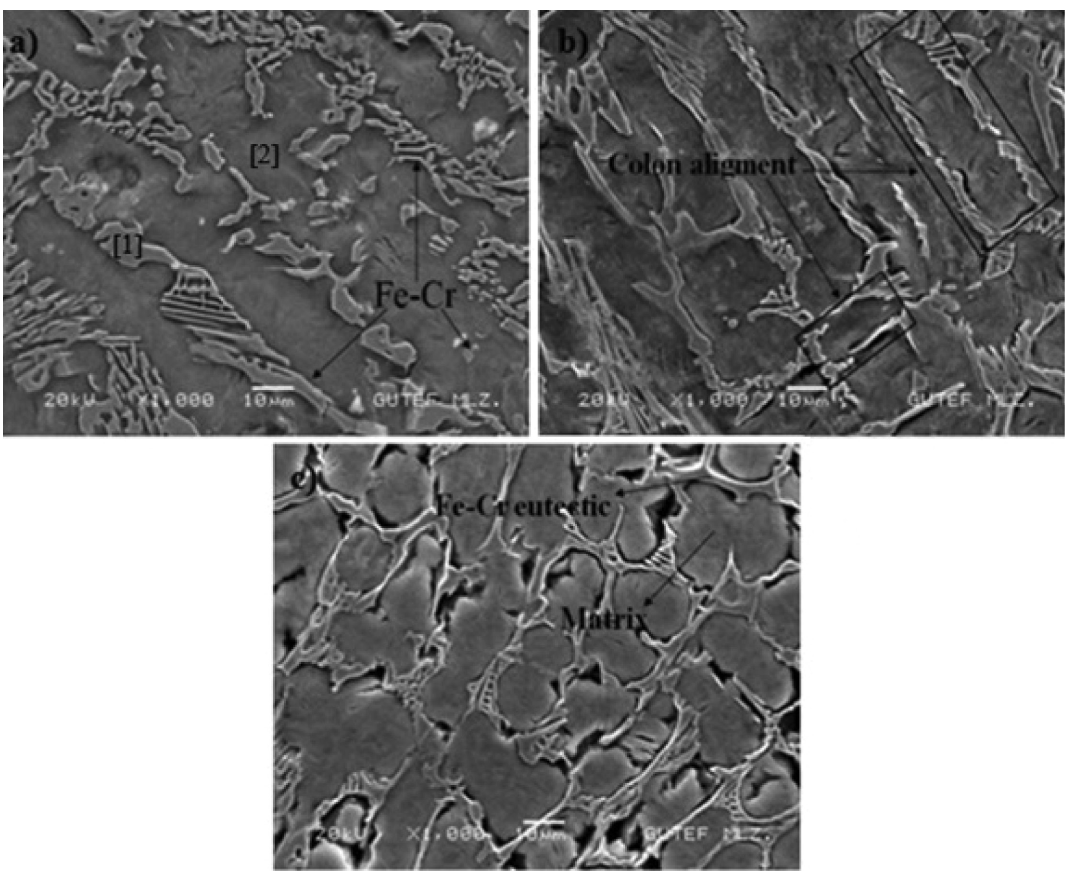


**Fig. 3:** SEM images of valve seat inserts with three different chemical compositions, (a) 10% Cr, (b) 12% Cr, and (c) 14%.

**Table 2:** Results of EDS analysis of 10% Cr specimens

| Location | Si | S | O | Mn | C | Cr | Fe |
|---|---|---|---|---|---|---|---|
| 1 | 1.205 | 1.673 | – | 3.336 | – | 41.733 | 51.731 |
| 2 | – | 0.560 | 10.113 | – | 8.159 | 27.586 | 53.082 |

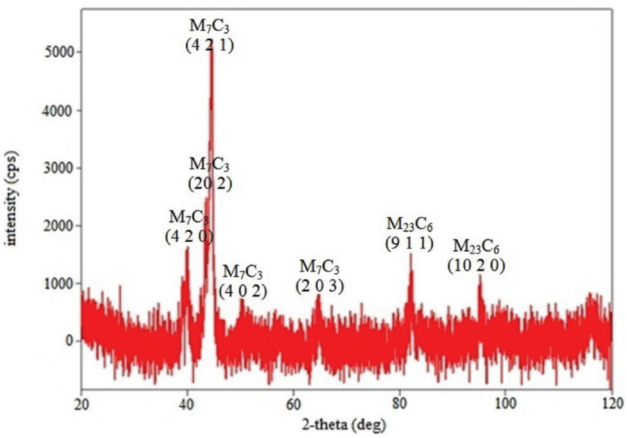


**Fig. 4:** XRD results of the alloy contain 10% Cr

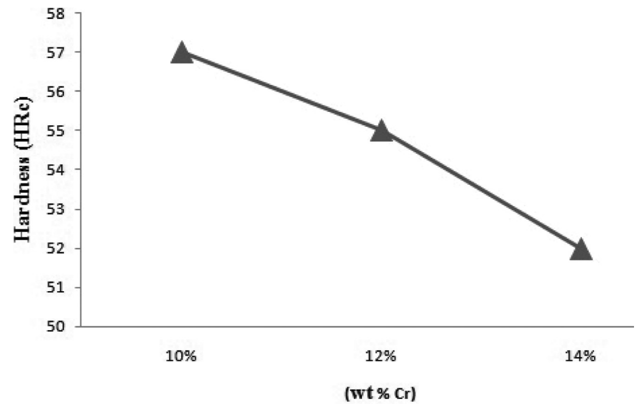


**Fig. 5:** Hardness of (10% Cr–12% Cr–14% Cr contained) samples

dominant. $M_7C_3$ and $M_{23}C_6$ carbides influence the mechanical properties, especially the wear behaviour of materials [8].

Microstructural features like the carbide type, hardness, volume fraction of the carbide, carbide dispersion and matrix structure play an important role in the wear behaviours of high chromium white irons. However, the relationship between the microstructure and wear behaviour is complex (for instance, the increasing volume fraction of the carbide is considered to be both useful and harmful for the wear behaviour) [15]. High chromium white iron alloys contain not only chromium, but also other elements forming carbide such as molybdenum, titanium and vanadium. Generally, the chromium carbides formed in the structure during the casting processes play an important role in the determination of alloy's properties. The amount of chromium that plays an important role in the formation of carbides is associated with the Cr/C rate of the alloy (For instance, when the Cr/C rate of the alloy is three, $M_7C_3$ type carbides are formed) [16].

## 3.3 Hardness results

Valve seat inserts of tappets provide motion in engines and function under heavy conditions in cylinders. For this purpose, one of the most important features investigated in valve seat inserts of tappets is the hardness values of alloys used in the production of valve seat inserts. Figure 5 gives the hardness variation depending on the Cr content of the samples.

From the hardness results given in Figure 5, it is seen that the highest hardness value is seen for the high chromium white iron alloy containing 10% Cr with 57 HRc. On the other hand, the lowest hardness value is seen for the alloy containing 14% Cr with 52 HRc, and a 55 HRc hardness value is seen for the alloy containing 12% Cr. In other words, according to the hardness results, as the chromium content increases in the alloy, the hardness of the alloy decreases. However, the hardness value of the alloy was expected to increase in parallel with the increasing Cr content before the experimental studies. Thus, the results of the hardness measurements were repeated for several times. However, the results did not change. The repeated hardness measurement just confirmed that the hardness decreased in parallel with the increasing amount of Cr. As a result of the XRD examinations, it was determined that this condition was apparently caused by the transformation in the carbide structure of $M_7C_3$ and $M_{23}C_6$. A previous study also reported that $M_7C_3$ carbides were harder than $M_{23}C_6$ carbides [17]. This transformation in the structure caused by the increasing amount of Cr apparently decreases the hardness of the alloy.

## 3.4 Wear tests

The superior wear resistance of high chromium white iron is a direct result of its microstructure. This high wear resistance is provided by solidification, as well as the forms of austenitic dentrides and high volume rates of $M_7C_3$ carbides present in the austenitic matrix [14, 18]. Figure 6 shows the weight losses of white irons used in the production of valve seat inserts of tappets and have various amounts of Cr. These curves were obtained under a load of 120 N and for various sliding distances up to 3000 m.

From the results of the weight losses given in Figure 6, it is seen that the greatest weight loss is seen for the alloy containing 14% Cr under heavy performance conditions (under a load of 120 N) and at the end of a sliding distance of 3000 m. On the other hand, the lowest weight loss is observed for the alloy containing 10% Cr. The weight loss

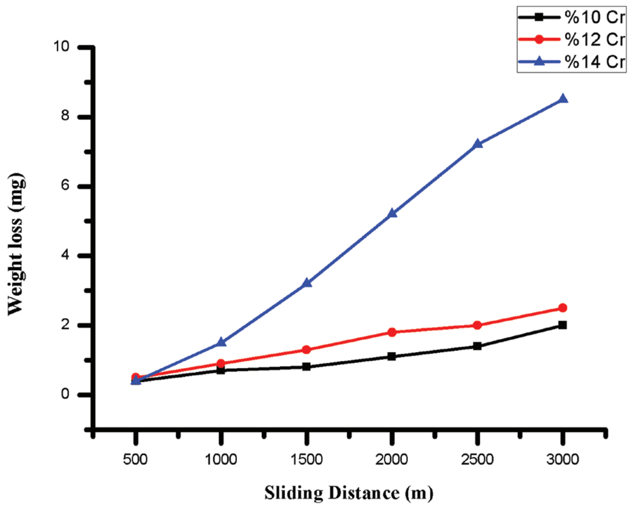


**Fig. 6:** Weight loss variations of high chromium white irons with different chromium contents under a load of 120 N

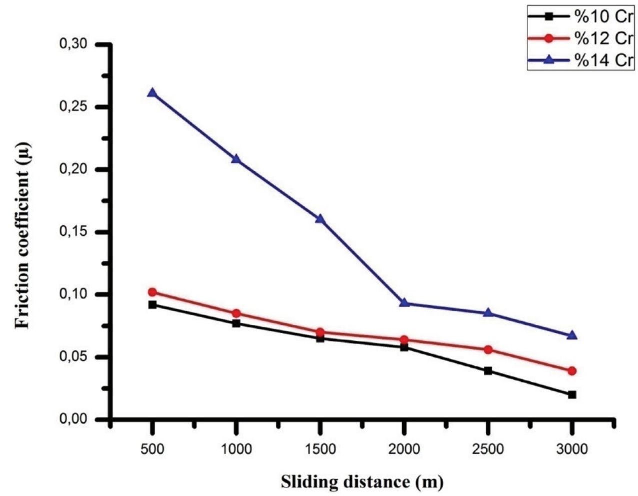


**Fig. 7:** The friction coefficients of samples worn at a sliding distance of 3000 m and under a load of 120 N

of the alloy containing 12% Cr was determined to have a value between those of two other alloys. When the weight losses and the hardness values given in Figure 5 are correlated, it is seen that the weight loss and hardness results support each other. Accordingly, the carbide transformations (from $M_7C_3$ carbides to $M_{23}C_6$ carbides) observed in the structure of high chromium white iron due to the increasing chromium content increased the wear under heavy performance conditions. Thus, the deformation as a result of the applied load under heavy performance conditions causes an increase in the weight loss. The increasing volume of $M_7C_3$ decreases the deformation of the metal matrix [19]. Similarly, according to the weight loss results given in Figure 6, it is seen that the amount of weight loss is lower at the sliding distance of the first 500 m, compared to the weight losses recorded all the way. One of the previous studies reported that $M_7C_3$ carbides displayed a brittle behaviour under heavy performance conditions (under a load of 152 N and 190 N) [20]. However, this present study showed that increasing $M_{23}C_6$ carbides as the result of increasing Cr increased the weight losses. When the weight loss results of this study and those of Atabaki et al. [20] are compared, it is seen that the results do not agree. The differences between the results can be attributed to the more brittle behaviour of $M_7C_3$ carbides than that of $M_{23}C_6$ carbides in applications above a certain critical points. It was considered that this brittle behaviour increases the weight loss. The friction coefficients displayed by the samples are given in Figure 7.

According to the results of the friction coefficients given in Figure 7, while the highest friction coefficient values were obtained from the samples containing 14% Cr, the lowest friction coefficient values were obtained from the alloy containing 10% Cr. When the obtained friction coefficient results in Figure 7 are correlated with the hardness results given in Figure 5 and the weight loss results given in Figure 6, it is seen that the results are consistent between each other. The alloy containing 10% Cr, having the highest hardness, was determined to also have the lowest weight loss and the lowest friction coefficient at the end of the wear tests. It is seen that the results obtained as a result of the wear tests show a good agreement with the results of some previous studies [21–23]. Figure 8 shows the SEM images of the worn surface of high chromium white iron alloys with different chromium contents.

The wear direction is seen clearly from the SEM images of the worn surfaces given in Figure 8. Plastic deformation on the worn surfaces of the three alloys containing different amounts of Cr is seen. The SEM images of samples show a very little amount of thin micro fractures caused by the plastic deformation on the worn surfaces. Additionally, it is observed that the particles separating from the sample and abrasive disc surfaces under the effect of friction were carried and adhered to the surface at different points under the effect of heat.

## 4 Conclusions

High chromium white irons containing three different chromium amounts (10%–12%–14%) were subjected to wear tests under a load of 120 N and at a sliding distance of 3000 m. It was determined that increasing amount of chromium in the material decreased the hardness and wear resistance of the materials. $M_7C_3$ carbides present in the material with a lower amount of chromium were found

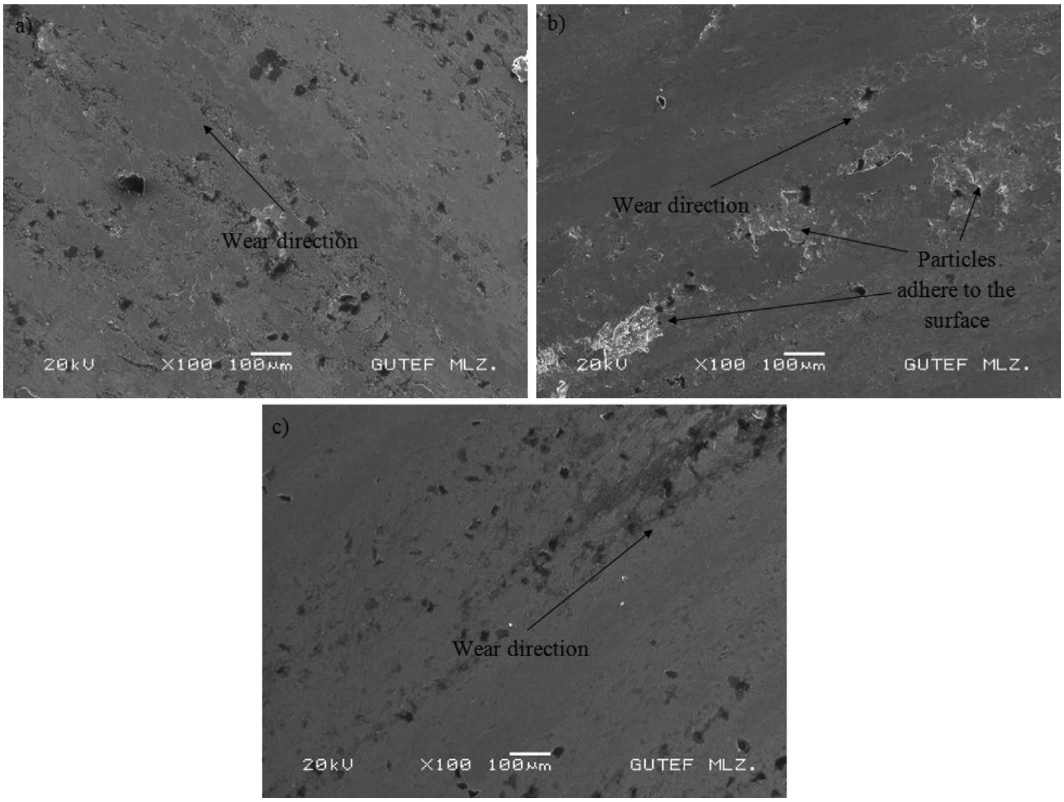


**Fig. 8:** SEM image of worn surface (a) 10% Cr, (b) 12% Cr and (c) 14% Cr

to be more resistant to wear. It was seen that the transformation of $M_7C_3$ carbides into $M_{23}C_6$ carbides due to the increasing amount of chromium in the material increased the weight loss. As a result of the wear tests, it was observed that the white iron containing higher amount of $M_{23}C_6$ carbides in the structure and 14% Cr was worn more than the others. In addition to this, the SEM images of the worn surface showed that particles separating from the surface were carried and then adhered to different points on the sample surface. As a result of the studies, it was also determined Cr amount in the high chromium white irons influenced the wear behaviour.

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