Microstructure and Wear Characteristics of Hypoeutectic, Eutectic and Hypereutectic (Cr,Fe)$_{23}$C$_6$ Carbides in Hardfacing Alloys

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This study investigates the microstructure and wear characteristics of hypoeutectic, eutectic and hypereutectic (Cr,Fe)$_{23}$C$_6$ carbides in hardfacing alloy cladding by using gas tungsten arc welding (GTAW). Chromium and graphite alloy fillers were used to clad ASTM A36 steel substrates. These coatings were specially designed to vary the size and proportion of the (Cr,Fe)$_{23}$C$_6$ carbides that are present in the microstructure at room temperature. Depending on the amount of graphite used in the alloy filler, a hypoeutectic, eutectic or hypereutectic microstructure was obtained on the coated surface. The wear behavior indicated that the abrasive wear resistance is not only simply related to the hardness of the deposit but that it is also determined by the carbides and matrix structure of the coating. The hypereutectic carbides have the largest (Cr,Fe)$_{23}$C$_6$ carbide content and the maximum hardness; however, they show the worst wear resistance due to the large particles were dug out during wearing. [doi:10.2320/matertrans.MB200716]

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1. Introduction

Hardfacing alloys are used under the conditions of extreme erosion and abrasive wear. The exceptional abrasive and erosive wear resistance characteristics of hardfacing alloys results primarily from their high volume fraction of hard carbides, although the toughness of the matrix also contributes to the wear resistance.

Observations of Fe-Cr-C alloys of Fe-Cr-C alloy microstructures have shown that these types of materials contain hypoeutectic, eutectic and hypereutectic structures.$^{1,3}$ M$_7$C$_3$ primary carbides are formed in large amounts at higher carbon concentrations. These types of microstructures have good wear resistance properties.$^{2,3}$

Fe-12~35Cr-C white cast irons are used as hardfacing alloys; these alloys have a high hardness value due to their high M$_7$C$_3$ content.$^{4,7}$ M$_7$C$_3$ is surrounded by austenite, which is relatively soft in comparison to the extremely hard M$_7$C$_3$. Consequently, cracks propagate along the interface between austenite and M$_7$C$_3$. This causes a serious problem for hardfacing materials.

Fe-28Cr-C hardfacing alloys are also used commercially for components that are subject to harsh abrasive conditions. The large amounts of carbides present in their microstructures consist of M$_7$C$_3$. They can be described as composites with large and extremely hard carbides in a softer body-centered-cubic (bcc) Cr-Fe alloy matrix.

Hardfacing alloys obtained using high-energy density sources such as electron beam welding, plasma arc and lasers have been widely applied in the industry to enhance the wear and corrosion resistance of the surfaces of underlying materials.$^{8-10}$

The criteria used for selecting the welding surface for wear and hardness applications depends on the features of its microstructure.

In this investigation, the gas tungsten arc welding (GTAW) process is employed to form a Fe-Cr-C hard surface with high chromium content over the ASME A36 steel with chromium and graphite alloy fillers. The changes in the microstructures and the wear characteristics of the coated surfaces were studied in detail by using an optical microscope (OM), a field emission scanning electron microscope (FE-SEM), an electron probe micro analyzer (EPMA), an X-ray diffractometer (XRD) and a dry sand rubber wheel abrasion tester.

2. Experimental Procedures

2.1 Specimen preparation

The substrate material for the welding surface was prepared from ASTM A36 steel plates with dimensions of 40 mm × 40 mm × 10 mm.

In order to obtain hypoeutectic, eutectic and hypereutectic (Cr,Fe)$_{23}$C$_6$ structures, different amounts of graphite and chromium powder were mixed together. The compacts of different powder mixtures were then prepared by a constant high pressure of 1500 psi (105.39 kg/cm$^2$) in order to form alloy filler with dimensions of 30 mm × 25 mm × 3 mm. The components of the three alloy fillers used in this study are listed in Table 1.

Bead-on-plate welding was accomplished by means of oscillating GTAW process by using electric power supply along with an auto-mechanized system in which the welding torch was moved back and forth at a constant speed above the alloy filler. The ranges of the welding conditions used in this research study are listed in Table 2.

2.2 Characterization of coating

The XRD specimens (12 mm × 12 mm) were prepared from the top surface of the hard-facing alloys. XRD with Cu
Kα radiation (0.154056 nm) was used to analyze the constituent phases in the microstructure.

The microstructures of the alloys were examined by using both OM and FE-SEM. The microstructure investigations were carried out on the top surface of the coatings after polishing and etching. The etchant was composed of 20 g of ammonium hydrogen fluoride, 0.5 g of potassium pyrosulfite and 100 mL of H₂O at 80°C.

An EPMA was utilized to analyze the chemical composition of the hardfacing alloys. The bulk hardness of their top surface was measured.

2.3 Wear test

Wear resistance experiments were conducted using an ASTM G-65 dry sand rubber wheel abrasive testing apparatus. The dry sand rubber wheel abrasion test is widely used to evaluate the low-stress abrasive wear of materials, particularly for the evaluation of wear-resistant materials used in mining and agricultural machinery industries.

Prior to the wear test, the abrasive wear test specimens were ground by using 800 mesh emery paper. Subsequently, quartz sand with size ranging from 300–200 μm was used. The sand flow rate was approximately 250 g/min, and the test load during the wear test was chosen to be 13.5 kg.

The speed of the dry sand rubber wheel in the abrasion test was set as 200 rpm. The weight loss was measured to within 1 mg. The wear specimens were thoroughly cleaned and washed, and their worn surfaces were observed under an OM to characterize the surface morphology and to study the possible mechanism for material removal.

3. Results and Discussion

Surface modification using GTAW and hardfacing alloy cladding is a process in which chromium and graphite alloy fillers of desirable compositions and a surface layer of the substrate material are simultaneously melted and then rapidly solidified to form a dense coating that is bonded to the base material. In this study, the substrate material used was carbon steel. Consequently, in addition to chromium and carbon, the hardfacing layer also had iron, which resulted in the formation of Fe-Cr-C alloys. No crack formation was observed, and the melted surface showed a smooth rippled surface topography. Figure 1 shows the morphology of the hardfacing layer. The thickness of the available coatings with different carbon compositions ranged from 2–3 mm.

Figure 2 shows the XRD spectrum of the surface of the hardfacing alloys. Specimens A and B were observed to contain a solid solution of Cr-Fe with the bcc crystal structure (α phase) and (Cr,Fe)₂₃C₆ with a complex fcc crystal structure. Specimen C was observed to contain three phases, i.e., α, (Cr,Fe)₂₃C₆, and trace amounts of (Cr,Fe)₇C₃.

Figures 3(a) and 4(a) show the microstructure of 5 mass% graphite. A primary Cr-Fe solid solution matrix (α) and a fine eutectic structure (M₅₃C₆ + α) are formed. Its hypoeutectic structure, eutectic is surrounded by the matrix. When the graphite composition reaches 7 mass%, the main carbide precipitate is M₅₃C₆. The microstructure in specimen B (7 mass%, graphite) is an (M₅₃C₆ + α) eutectic structure, as shown in Figs. 3(b) and 4(b). In the solidification process of GTAW, the Fe-Cr-C alloy eutectics grow uniformly in all directions until finally an equi-axed dendrite structure is obtained. Comparing Figs. 4(a) and 4(b), the eutectic grain is observed to be coarser than the hypoeutectic grain, which is due to the different solidification rates for each hardfacing alloy.
The microstructures obtained from specimen C are presented in Figs. 3(c) and 4(c). It is evident that the primary phases, as shown in Fig. 4(c), are coarser than those shown in Figs. 4(a) and 4(b). A comparison among Figs. 4(a), 4(b) and 4(c) shows that increasing the amount of graphite powder promotes the formation of (Cr,Fe)$_{23}$C$_6$ carbide. This type of structure is similar to the eutectic structure of a casting in high-carbon ferrochromium.\textsuperscript{14)

The (Cr,Fe)$_7$C$_3$ carbides are generally covered with other phases, which make it almost impossible to identify them with an OM. In this study, it was observed clearly on a back-scattered electron image (BEI) of the FE-SEM by their different element concentration. This results in an apparent contrast in the BEI image, as shown in Fig. 5. The dark area represents (Cr,Fe)$_7$C$_3$ and the gray area represents (Cr,Fe)$_{23}$C$_6$.

The chemical composition of hardfacing alloys was analyzed by EPMA and the results are listed in Table 3. The analyses were carried out for the surface of the specimen. The compositions of hardfacing alloys A, B and C are listed in Table 3. Based on this liquidus projection, the structures of specimens A, B and C correspond to Cr-Fe solid solution (\(\alpha\)), eutectic (\(\alpha + M_{23}C_6\)) and \(M_{23}C_6\). Microstructure of specimen A constructed from the Cr-Fe solid solution matrix and a fiber-like (Cr,Fe)$_{23}$C$_6$ carbide (a hypoetuctic structure), as shown in Fig. 4(a). (Cr,Fe)$_{23}$C$_6$ was the first to appear following the commencement of the solidification of hardfacing alloy C. Subsequently, an irregular and coarse
The eutectic structure was formed around the \((\text{Cr,Fe})_23\text{C}_6\) grain boundary, as shown in Fig. 4(c).

The hardness measurements performed for the hardfacing alloys with different graphite contents are shown in Fig. 6. It is evident that the maximum hardness values were obtained for the surface of the hardfacing alloy cladding of specimen C. This increase in hardness of the alloyed surface of specimen C is associated with the large amounts of \((\text{Cr,Fe})_23\text{C}_6\) and \((\text{Cr,Fe})_7\text{C}_3\), which possess high carbon content as compared to the other two specimens.

Figure 7 shows the wear loss of each specimen after being subjected to the dry sand rubber wheel abrasive test. It shows that the wear loss increases with the wear time. The wear resistance of hardfacing alloys C is the worst among the wear resistance of all the alloys, even if the appear of thick and big \((\text{Cr,Fe})_23\text{C}_6\) and trace \((\text{Cr,Fe})_7\text{C}_3\) carbide lead specimen C have the highest hardness (as shown in Fig. 6). The fine \((\text{Cr,Fe})_23\text{C}_6\) structure has a greater effect on the wear resistance as compared to the coarse \((\text{Cr,Fe})_23\text{C}_6\) structure.

An examination of the wear scars indicated that the damage morphologies for all the samples were different, as shown in Fig. 8. The scar in specimen A was the finest (Fig. 8a) and the wear loss of the specimen was the least (Fig. 7). In addition, Figs. 3(c) and 4(c) show that the hypereutectic structure comprises a coarse hypereutectic structure and a large amount of \((\text{Cr,Fe})_23\text{C}_6\) carbide. This arrangement allows the hypereutectic structure to shed easily from the coatings because of the unsuitable combination of the massive carbide and the coarse \((\text{Cr,Fe})_23\text{C}_6\)/Cr-Fe eutectic structure. Pits can be observed (the shadow under the scars) in Figs. 8(b) and 8(c). Furthermore, the pits in specimen C are larger than those in B. Moreover, specimen C has few scars but has holes produced during the wear test. As a result, the wear loss becomes larger than the wear losses of the hypoeutectic and eutectic specimens, and a very rough surface is formed, as shown in Fig. 8(c). Thus, it is assumed that the wear is due to the progress of abrasive particles by preferentially abrading the matrix due to their abrasion, thereby gradually penetrating and corroding the matrix. This action gradually increases the carbide content, and consequently the carbides must support the load of the abrasive particles. By increasing the fineness of the carbides, the force from the abrasive particles is reduced, which improves the abrasion resistance. However, if the preferential wear of the matrix regions is excessive, then the carbides are no longer supported and they become susceptible to spalling and fracture.

In general, the two components of wear resistant materials serve different functions. The hard particles impede the wear by grooving or indenting the mineral particles, while the metal matrix provides sufficient toughness. Both properties depend on the amount, size and distribution of the hard particles as well as the hardness and fracture toughness of both the components and the bond between them.

4. Conclusions

In this study, the quantity of graphite was adjusted to
obtain three types of structures: hypoeutectic, eutectic and hypereutectic. These structures consisted of carbides with different morphologies and matrices. The abrasive wear results show that the morphology of (Cr,Fe)$_{23}$C$_6$ carbides have a large effect on the abrasion resistance of the coating. The coarser the (Cr,Fe)$_{23}$C$_6$ carbides, the lower is the wear resistance, even if the large (Cr,Fe)$_{23}$C$_6$ carbides appropriately contribute to the hardness of the hardfacing layer. Furthermore, the wear behavior indicated that the abrasive wear resistance is not only simply related to the hardness of the deposit but also determined by the carbides and the matrix structure of the coating. Fine and highly-concentrated carbide is better than a large amount of carbide in an abrasive wear test because a thick and large structure causes large particles but not scars to be dug out during wearing.

REFERENCES


Fig. 8 OMs of the hardfacing alloys after being subject to wear for 30 min: (a) hypoeutectic structure, (b) eutectic structure and (c) hypereutectic structure.