Sliding wear resistance of iron aluminides

GARIMA SHARMA, M SUNDARARAMAN*, N PRABHU[†] and G L GOSWAMI[‡]

Materials Science Division, [‡]Atomic Fuels Division, Bhabha Atomic Research Centre, Mumbai 400 085, India

[†]Department of Metallurgical Engineering and Materials Science, Indian Institute of Technology, Mumbai 400 076, India

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Abstract. Room temperature dry sliding wear behaviour of iron aluminides containing 28% aluminium and various amounts of chromium has been investigated using pin on disk wear tester. The aluminides were heat treated to have ordered DO_3 structure. It was found that wear rate of the aluminides increased with the increase of applied normal load and sliding speed. Wear resistance of the aluminides increased with increase in chromium content. SEM observation of the worn surface showed that the microcutting and microploughing were the dominant sliding wear mechanisms.

Keywords. Iron aluminide; sliding wear; wear; intermetallics; Fe_3Al ; ordered structures.

1. Introduction

The failure of components in service can often be attributed to wear, erosion or corrosion-enhanced wear and erosion. The phenomenon contributing to failure under all these conditions are complex and often specific to the particular application. Material properties determining resistance to wear and erosion are correspondingly complex, making it difficult to predict the service behaviour of a particular material. Generally, high hardness, rapid work hardening, and good oxidation and corrosion resistance can all contribute to wear and erosion resistance (Preece 1979). Common materials currently used in severe wear and erosion applications include cobalt-based alloys, high manganese stainless steels, and other chromium containing alloys. There is considerable interest in replacing cobalt-based alloys for erosion resistance in nuclear power applications because of the problems with exposure of maintenance workers to induced radiation in the debris from the erosion and corrosion of these alloys.

Iron aluminides based on $B2$ or DO_3 ordered Fe_3Al based alloys are now receiving extensive attention as materials with good potential for industrial applications as replacement for high temperature oxidation resisting or corrosion resisting stainless steel (McKamey *et al* 1988, 1991; McKamey and Liu 1990; Sikka 1991). The lack of ductility at room temperature and a decrease in strength above 873 K had retarded their development as a structural material. However, improvement in the room temperature ductility of Fe_3Al has been achieved recently by the addition of alloying elements such as chromium (Lawley *et al* 1960; Sikka 1991; McKamey *et al* 1992). Efforts are continuing to develop iron aluminides for

high temperature structural applications. Much effort has gone into structure control for improving and optimizing the mechanical properties of Fe_3Al based alloys. Only a few investigations have reported to date the wear characteristics of the iron aluminide, which is an important ordered intermetallic alloy (Johnson *et al* 1990, 1994, 1996; Maupin *et al* 1992, 1993; Tu and Liu 1997; Kim and Kim 1998). Maupin *et al* (1992, 1993) had shown that the Fe_3Al alloy having DO_3 structure possesses marginally lower wear rate than those with $B2$ structure. The wear resistance of Fe_3Al alloy was found to vary with ductility and yield strength. It was found that the addition of aluminum to iron in Fe_3Al alloy has the effect of improving the wear resistance compared with that of pure iron whether the alloy is ordered or not. Moreover, the reported works on wear deal with only abrasive and erosive wear of the alloy as a function of varying aluminium content (Maupin *et al* 1992; Kim and Kim 1998). The abrasive wear resistance of Fe_3Al alloy was found to be comparable with the wear resistance of AISI 1060 carbon steel and SS 304 (Maupin *et al* 1992, 1993). The abrasive wear of Fe_3Al compares favourably with that of Hadfield steel, a high toughness material used in the mining applications. Some work had also been reported on the sliding wear behaviour of Ni–Al intermetallic compounds (Marquardt and Wert 1985; Blau and DeVore 1988). The present paper reports the effect of ternary element addition of chromium on the room temperature dry sliding wear behaviour of iron aluminides. SEM investigation of wear surfaces was employed to study the wear mechanisms in these specimens.

2. Experimental

Pins for wear tests were prepared by machining $3 \times 3 \times 20$ mm cross-section specimens from vacuum induction

*Author for correspondence

melted cast material with three different compositions. The compositions of the alloy chosen for this study were Fe-28Al (at.%), Fe-28Al-3Cr (at.%) and Fe-28Al-5Cr (at.%). The pins were homogenized at 1000°C for 4 h and then heat treated at 540°C for 170 h followed by furnace cooling to obtain DO_3 structure. The heat-treated samples were polished to have an initial centre line average surface roughness (R_a) of 0.32 μm .

Microhardness measurements were made on the heat treated, polished samples using a microhardness tester with Knoop indenter (table 1). Sliding wear tests were carried out in air at room temperature on a pin-on-disk apparatus. The disk was covered with abrasive paper of grit size 240. This corresponds to an abrasive particle size of about 200 μm . Pin was pressed on the disc with two different normal loads (25 and 35 N). The wear tests were carried out at two different speeds (1.57 and 2.6 m/s). The wear data were collected after 0.5, 1 and 2 min. Sliding wear was determined from the change in the length of the pin using LVDT setup. This change in length was then converted to volume loss for each sample. All wear tests were repeated again and the average value was taken. After each wear test, the specimen surfaces were examined by optical and scanning electron microscope.

3. Results and discussion

Wear tests of the aluminides were performed with two different loads and speeds. The wear rates were calcu-

Table 1. Microhardness of the iron aluminides with three different compositions.

Sl. no.	Alloy	Microhardness (kg/mm ²) Load (500 g)
1	Fe-28Al	397
2	Fe-28Al-3Cr	378
3	Fe-28Al-5Cr	372

lated by dividing volume of wear by sliding distance. Wear rates vs sliding distance for different compositions of iron aluminides are shown in figures 1 (a-b) and 2 (a-b). These plots showed that wear rate decreased as the sliding distance increased. The increase in sliding speed from 1.57 m/s to 2.6 m/s resulted in an increase in wear rate at a constant load (figures 1 and 2). The aluminides tested with different loads showed a clear difference in the wear rates. The rate difference among the specimens became greater with an increase in the applied load from 25 to 35 N (figures 1 and 2). Sliding wear behaviour of iron-aluminides was found to decrease with increase in ternary element addition.

Table 1 shows clearly that the chromium addition reduces hardness of the alloy. This observation agrees with the results of Nishino *et al* (1997). Similar observations regarding the role of chromium addition on mechanical properties of Fe₃Al alloys containing 25% Al (Huang *et al* 2001) and 28% Al (McKamey *et al* 1989; Huang *et al* 2001) have been reported. In fact, an increase in aluminium content from 25 to 28% (at.%) resulted in decrease in hardness of Fe₃Al alloys (Kim and Kim 1998). They have also observed a simultaneous decrease in yield strength and an increase in work hardening rate with increasing aluminum content. This effect has been attributed to the effect of increase in aluminium content or ternary chromium addition on the antiphase boundary in DO_3 structure Fe₃Al alloys. Deformation of Fe₃Al alloys is facilitated by the movement of a group of four $a/4 \langle 111 \rangle$ dislocations, which is nothing, but unit dislocations of bcc structure with $a/2 \langle 111 \rangle$ Burgers vector (McKamey *et al* 1989). Two types of APBs are generated between leading and trailing pairs of dislocations and also in between these pairs. McKamey *et al* (1989) observed an increase in separation between all these dislocations with chromium addition, which is indicative of reduction in APB energy. Another consequence of this decrease in APB energy is the uncoupling of leading and

Figure 1. The variation of wear rate with sliding distance for different compositions of iron aluminides: (a) 1.57 m/s sliding speed and (b) 2.6 m/s sliding speed, at a constant 25 N load.

trailing pairs of dislocations in the case of chromium containing alloys. This could result in the ease of cross slip of dislocations resulting in higher ductility and work-hardening rate.

In the present study, the chromium addition showed an improvement in the wear resistance of Fe_3Al alloys (figures 1 and 2). These results are in good agreement with earlier reported results on the abrasive and erosive properties of iron aluminides containing chromium (Johnson *et al* 1994). On the basis of the discussion in the last paragraph, this improvement could be attributed to increased plastic deformation and work hardening rate of the alloys. Moreover, it has been reported in the literature that disordering of the surface occurs during sliding wear and disordered Fe_3Al alloys have been observed to have higher wear resistance than ordered Fe_3Al alloys due to dynamic recrystallization leading to nanocrystalline grains formation on the surface (Maupin *et al* 1992, 1993). All these phenomena, which occur during abrasion, seem to increase the wear resistance of the alloys with chromium addition.

The present observations regarding the decrease in wear rate with increase in sliding distance and increase in wear rate with increase in sliding speed as well as load [see figures 1 and 2] are in conformity with earlier studies on binary Fe_3Al alloys near stoichiometric compositions. This could be due to the combined effect of large friction heat generated as well as the work-hardening and subsequent dynamic recrystallization of the surface during sliding. Maupin *et al* (1992, 1993) showed that ordering was completely lost on the deformed surface and large grains were replaced by fine nanocrystalline grains, which were relatively free of dislocations. Such microstructures could develop only if the temperature of the surface due to friction is very high. Maupin *et al* (1992, 1993) have further determined that the flash temperature near asperities due to friction heat in Fe_3Al alloys due to their poor thermal conductivity could reach very high value, suffi-

cient to cause dynamic recrystallization of the deformed surface. They attribute the large increase in Knoop hardness with sliding distance to the fine sized grains developed on the surface. In addition, disordering of the surface layer could result in higher plastic flow and work hardening resulting in increased wear resistance. At such high temperature oxidation of the surface is also a possibility and in fact oxide layers have been observed in many worn surfaces of these alloys. From the above discussion, one could conclude that the wear rate should decrease with the sliding distance. Higher sliding speed induces higher deformation rate of the wearing surface, which seem to result in increase in wearing rate.

Examination of wear surfaces of iron aluminides by SEM in the present study indicated that microploughing, microcutting were the dominant sliding wear mechanisms (figures 3a and b). During microploughing, material may be ploughed aside repeatedly by passing particles and may break off. Similar observations were reported by Maupin *et al* (1992, 1993) where they found microploughing, microcutting and microfracture to be the dominant abrasive wear mechanism of iron aluminides. Johnson *et al* (1994) reported that microploughing and microcutting were the two dominant material removal processes during abrasion wear of iron aluminides. These mechanisms were responsible for the narrow, deep grooves on the worn surfaces of the abraded samples. However, Kim and Kim (1998) showed that under low load condition, microploughing was the predominant wear mechanism for iron aluminides, whereas under high load conditions, formation of platelets and their subsequent detachment from the wearing surface was observed as a dominant wear mechanism. In brittle or hard material, very few slip systems are available and during wear, strains accumulate at the surface resulting in the formation of subsurface deformation zone. Cracks initiate in this zone and the delamination of the zone results in higher wear rate. Iron aluminides did not show any sharply

Figure 2. The variation of wear rate with sliding distance for different compositions of iron aluminides: (a) 1.57 m/s sliding speed and (b) 2.6 m/s sliding speed, at a constant 35 N load.

Figure 3. (a) Microcutting mechanism at 35 N load, 2.6 m/s sliding speed in binary alloy and (b) microcutting and microploughing at 35 N and 2.6 m/s sliding speed in Fe-28Al-5Cr alloy.

delineated cleavage faces or the cracks of brittle nature on the wear surface (figures 3a and b). SEM examination in the present case indicated that microploughing and microcutting were the dominant wear mechanisms. This is indicative of the fact that considerable plastic deformation might have occurred on the surface. Based on these observations, it can be postulated that the wear mechanism of the iron aluminides was plastic deformation dependent.

4. Conclusions

The sliding wear behaviour of iron aluminides with different compositions had been evaluated in this study and the following conclusions were reached.

- (I) The sliding wear rate of iron aluminides was found to decrease with the increase in sliding distance. However, increase in the sliding speed resulted in an increase in a wear rate.
- (II) Iron aluminides modified with chromium additions showed higher sliding wear resistance than binary iron aluminides.
- (III) SEM examinations of the abraded surfaces indicated that microploughing and microcutting were the dominant sliding wear mechanisms and wear mechanism of the iron aluminides was plastic deformation dependent.

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