Tribology International 69 (2014) 61–69

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Friction and wear properties of $\alpha FeSi_2$–Si alloy, $ReSi_{1.8}$ and $MoSi_2$ in ethyl alcohol

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ARTICLE INFO

Article history:
Received 30 May 2013
Received in revised form
3 September 2013
Accepted 4 September 2013
Available online 12 September 2013

Keywords:
Silicides
Spark plasma sintering
Ethanol
Boundary lubrication

ABSTRACT

In this study, Fe–X at% Si alloy (X=70.5, 80.0 and 96.0), Re–64.3 at% Si and Mo–66.7 at% Si disk specimens were prepared by spark plasma sintering, and their friction and wear properties were investigated when they were slid against Si_3N_4 ball specimens in ethyl alcohol. The friction and wear properties of Si ingots were also examined. Fe–70.5 at% Si, Fe–80.0 at% Si, Fe–96.0 at% Si and Re–64.3 at% Si disk specimens exhibited friction coefficients as low as 0.15. It is considered that the low friction of the Fe–70.5 at% Si, Fe–80.5 at% Si and Fe–96.0 at% Si disk specimens was due to the formation of low friction silicon alkoxide and polyoxysilane on the worn surfaces of the disk specimens and the paired ball specimens. Re–64.3 at% Si disk specimens exhibited the highest microvickers hardness of all the disk specimens prepared in this study. In addition, the microvickers hardness of the Fe–X at% Si (X=70.5, 80.0, 96.0 and 100) disk specimen increased with increasing the Si content. Moreover, it was difficult to obtain dense Fe–90.0 at% Si disk specimens by sintering the annealed and crushed Fe–90.0 at% Si powder. However, dense Fe–96.0 at% Si disk specimens could be obtained by sintering the Fe–90.0 at% Si powder at 1403 K.

1. Introduction

Bioethanol has recently attracted much attention in the automotive industry because CO_2 emissions can be reduced by using it as a fuel [1,2]. It is considered that such CO_2 emissions can be also reduced by changing cast iron cylinder liners with much lower friction material cylinder liners. However, the friction and wear properties of various kinds of sliding materials have not yet been investigated sufficiently when the lubricant is ethyl alcohol. It was found in our previous study that $\beta FeSi_2$ disk specimens with a composition of Fe–66.7 at% Si and $\alpha FeSi_2$ disk specimens with a composition of Fe–70.5 at% Si exhibited friction coefficients as low as 0.1 when sliding against Si_3N_4 balls in ethyl alcohol [3]. Hibi et al. reported that SiO_2 gel, silicon alkoxide ($Si(OR)_n(OH)_{4-n}$, where R is CH_3, C_2H_5, C_3H_7, C_4H_9, etc.), polyoxysilane ($(\text{–O–Si}(OR)_n(OH)_{2-n}\text{–O–})_m$), long-chain hydrocarbons were formed on the worn surface of Si_3N_4 specimens in short-chain n-alcohol by oxidation, mechanochemical reactions and other causes. They also described that the formation of the silicon alkoxide and polyoxysilane increased the viscosity of the solution, which might have caused the low friction coefficients (0.11–0.12) of Si_3N_4/Si_3N_4 tribopair [4,5]. These results indicate that Fe–Si alloys with high Si content may exhibit low friction coefficients and low specific wear rates. However, the friction and wear properties of Fe–Si disk specimens with Si content higher than 70.5 at% have not been investigated.

Also, it is considered that $ReSi_{1.8}$ and $MoSi_2$ may exhibit lower friction coefficients and lower specific wear rates than the $\alpha FeSi_2$ and $\beta FeSi_2$ disk specimens. Iron oxides and SiO_2 films were formed on the worn surfaces when Fe–Si alloys were slid in ethyl alcohol [3]. This occurred because the fleshly exposed sliding surface was rapidly oxidized by oxygen dissolved in ethyl alcohol [4]. It is considered that the surface of the SiO_2 film changes to low friction silicon alkoxide and polyoxysilane in ethyl alcohol, but the iron oxides may exhibit higher friction coefficients than rhenium oxides and MoO_3 [6]. The rhenium oxide and MoO_3 films may be formed on the worn surfaces of the $ReSi_{1.8}$ and $MoSi_2$ disk specimens, respectively.

In this study, we prepared Fe–Si disk specimens with high Si content, $ReSi_{1.8}$ and $MoSi_2$-based alloy disk specimens by spark plasma sintering (SPS) [7–9] and investigated their friction and wear properties sliding against Si_3N_4 ball specimens in ethyl alcohol using a ball-on-disk tribometer. SPS is a hot pressing process and the sample powder is heated by flowing an electric current through a graphite mold containing the powder. It has been reported that dense ceramic and metal powder compacts can be obtained very easily for very short sintering times using this process [7].

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http://dx.doi.org/10.1016/j.triboint.2013.09.002

Table 1
Sintering conditions of Fe–70.5 at% Si, Fe–80.0 at% Si, Fe–90 at% Si, Re–64.3 at% Si and Mo–66.7 at% Si disk specimens prepared in this study.

Composition	Sintering temperature (K)	Pressure (MPa)	Sintering time (ks)
Fe–70.5 at% Si	1323	40	0.6
Fe–80.0 at% Si	1383	70	3.6
Fe–96.0 at% Si	1403	40	0.6
Re–64.3 at% Si	1673	40	1.2
Mo–66.7 at% Si	1573	40	1.2

Table 2
Annealing conditions of Fe–70.5 at% Si, Fe–80.0 at% Si, Fe–90 at% Si and Re–64.3 at% Si blended powders prepared in this study.

Composition	Annealing temperature (K)	Annealing time (ks)
Fe–70.5 at% Si	1373	172.8
Fe–80.0 at% Si	1373	172.8
Fe–90.0 at% Si	1373	172.8
Re–64.3 at% Si	1673	7.2

2. Experimental procedures

In this study, Fe–X at% Si (X=70.5, 80.0 and 96.0) and Re–64.3 at% Si disk specimens with a diameter of 20 mm and a thickness of 4 mm were prepared by spark plasma sintering the annealed and crushed Fe–Y at% Si (Y=70.5, 80.0 and 90.0) and Re–64.3 at% Si powders, respectively, under the conditions shown in Table 1. The annealed powders were prepared using the following procedures. 99.5% pure Fe powder with a particle size of 7–8 μm, 99.99% pure Re powder with a particle size of less than 45 μm and 99.99% pure Si powder with a particle size of less than 100 μm were blended in a hexane-filled standard ball mill and then the blended powders were annealed under the conditions shown in Table 2. After annealing, the annealed powders were crushed to a particle size of less than 45 μm using a stamp mill. Also, $MoSi_2$-based alloy disk specimens were prepared by SPS using commercial 99.5% pure $MoSi_2$ powder with a particle size of less than 45 μm under the conditions shown in Table 1. In addition, it was difficult to obtain dense Fe–90.0 at% Si disk specimens by sintering the annealed and crushed Fe–90.0 at% Si powder. When the sintering temperature was lower than 1393 K, the relative density of the Fe–90 at% Si disk specimen was less than 90%. On the other hand, the Fe–90.0 at% Si powder specimen partially melted when the sintering temperature was higher than 1393 K. Therefore, we obtained dense Fe–96.0 at% Si disk specimens by sintering the Fe–90.0 at% Si powder at 1403 K, and at this temperature the powder specimen partially melted and the melt flowed out of the graphite mold. After this sintering, EDS analysis showed that the composition of the dense disk specimen remaining in the graphite mold was Fe–96.0 at% Si. We used this dense disk specimen as "Fe–96.0 at% Si disk specimen" in this study. Moreover, Si ingot disk specimens with a purity of 99.999% were prepared for the friction and wear tests performed in this study.

After the spark plasma sintering, the surface of each disk specimen was polished using 4000-grit SiC papers. Then all of the disk specimens were cleaned in a mixture of 50 vol% acetone and 50 vol% petroleum benzene using an ultrasonic cleaner for 1.2 ks. The microvickers hardness of each disk specimen was examined at a load of 9.8 N and a loading time of 15 s because a lot of materials exhibit some relationships with their hardness.

The friction and wear properties of each disk specimen sliding against the Si_3N_4 ball specimens were investigated using a rotating

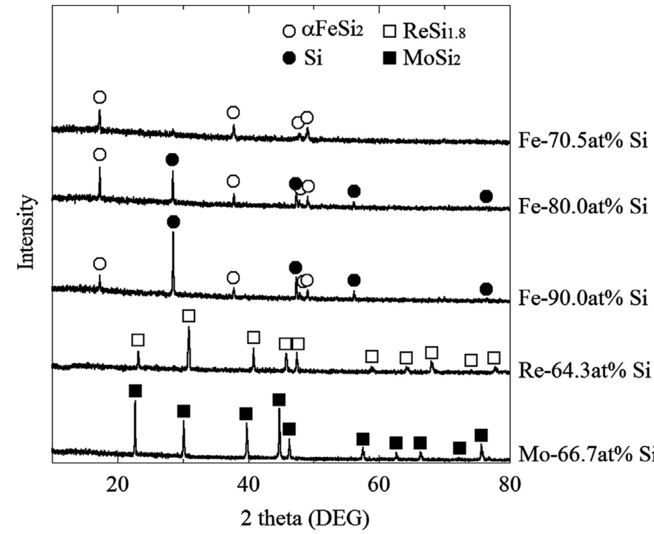

Fig. 1. XRD patterns of Fe–Y at% Si (Y=70.5, 80.0 and 90.0), Re–64.3 at% Si and Mo–66.7 at% Si powders used for SPS in this study.

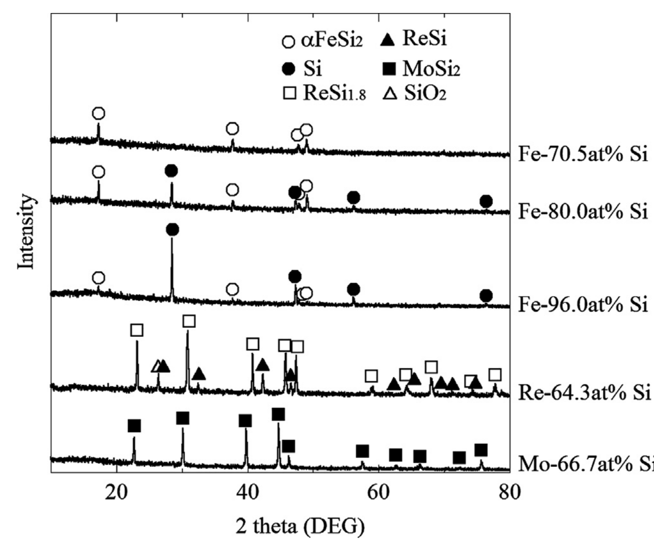

Fig. 2. XRD patterns of Fe–X at% Si (X=70.5, 80.0 and 96.0), Re–64.3 at% Si and Mo–66.7 at% Si disk specimens prepared in this study.

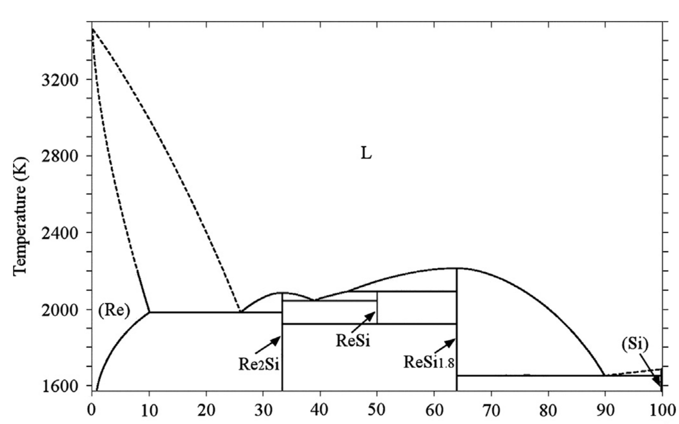

Fig. 3. Re–Si binary phase diagram reported by Gokhale et al. [9].