Tribological Properties of Nanostructured Al/Al₁₂(Fe,V)₃Si Alloys

Hamid Ashrafi · Mohammad Hosein Enayati · Rahmatollah Emadi

Received: 14 April 2014 / Revised: 27 June 2014 / Published online: 20 November 2014
© The Chinese Society for Metals and Springer-Verlag Berlin Heidelberg 2014

Abstract Tribological behavior of nanostructured pure Al and Al–Al₁₂(Fe,V)₃Si alloys containing 27 (FVS0812) and 37 (FVS1212) vol% of Al₁₂(Fe,V)₃Si precipitates was investigated. All samples were prepared using mechanical alloying followed by hot pressing. Wear tests were performed at room temperature using a pin-on-disk machine. Results showed that the presence of Al₁₂(Fe,V)₃Si precipitates increases the wear resistance of nanostructured Al, and the wear resistance increases with increasing the Al₁₂(Fe,V)₃Si content. Scanning electron microscopy images of worn surfaces and wear debris demonstrated that abrasion and adhesion are the governing wear mechanisms for the nanostructured FVS0812 alloy at 2 and 5 N normal loads, whereas for the nanostructured FVS1212 alloy, the dominant wear mechanism is abrasion at these loads. A mechanically mixed layer (MML) containing Fe and O was formed on the worn surfaces of FVS0812 and FVS1212 samples at 10 N normal load. Formation and delamination of MML controls the wear behavior of these samples at the normal load of 10 N. It is also found that the presence of Al₁₂(Fe,V)₃Si precipitates decreases the friction coefficient of nanostructured Al.

KEY WORDS: Al–Fe–V–Si alloy; Wear; Scanning electron microscopy

1 Introduction

Aluminum is an attractive material for industrial applications because of its light weight, high thermal and electrical conductivities, and good corrosion resistance. However, aluminum by itself has poor tribological behavior [1]. Therefore, numerous efforts have been made to improve the tribological behavior of aluminum-based materials to suitable levels for tribological applications. These studies mainly focused on reinforcing with hard ceramic [2, 3] or intermetallic [4] particles and grain refinement [5].

Nanostructured materials have been the subject of intensive study over the past years because of their improved properties compared with conventional coarse-grained materials [6]. However, tribological properties of nanostructured materials were rarely studied owing to the difficulty of producing bulk samples suitable for wear tests [7]. Salehi-kahrizangi et al. [8] compared the tribological properties of commercial Ti6Al4 V alloy with those for nanostructured Ti6Al4 V alloy produced via a powder metallurgy method. They found that the nanostructured alloy has lower wear rate compared with the commercial alloy, while the friction coefficient is almost equal. Abrasive and adhesive wear were the governing wear mechanisms for both the commercial and the nanostructured alloys. Jafari et al. [9] studied the wear behavior of bulk nanostructured Al2024 alloy produced by mechanical alloying (MA) and hot pressing (HP) methods. They indicated that the wear rate of nanostructured Al2024 alloy is 92.5 and 85.4 % lower than that obtained for Al2024–O and Al2024–T6 alloys, respectively.

Available online at <http://link.springer.com/journal/40195>

H. Ashrafi (✉) · M. H. Enayati · R. Emadi
Department of Materials Engineering, Isfahan University of
Technology, Isfahan 84156-83111, Iran
e-mail: h.ashrafi@ma.iut.ac.ir

Table 1 Chemical compositions of the samples

Sample	Chemical composition (wt%)	Nominal $\text{Al}_{12}(\text{Fe,V})_3\text{Si}$ content (vol%)
Al	Pure Al	0
FVS0812	Al-8.5Fe-1.3 V-1.7Si	27
FVS1212	Al-11.6Fe-1.3 V-2.3Si	37

$\text{Al}_{12}(\text{Fe,V})_3\text{Si}$ intermetallic compound is a metastable phase which is formed in Al–Fe–V–Si alloys after rapid quenching with high cooling rates [10]. Rapidly solidified Al/ $\text{Al}_{12}(\text{Fe,V})_3\text{Si}$ two phase alloys with high fraction $\text{Al}_{12}(\text{Fe,V})_3\text{Si}$ precipitates (27–37 vol%) are known to have good mechanical properties both at room temperature and high temperatures. The $\text{Al}_{12}(\text{Fe,V})_3\text{Si}$ intermetallic compound is responsible for the good properties of these alloys [11, 12]. Although many properties of Al/ $\text{Al}_{12}(\text{Fe,V})_3\text{Si}$ alloys have been studied in detail, but their tribological properties have not been addressed so far. Yang *et al.* [13] investigated the wear performance of A201 composite reinforced with the 60 vol% of rapidly solidified Al–Fe–V–Si alloy particles produced via an infiltration method. They found that in comparison with the monolithic A201 alloy, this composite has higher wear rate and friction coefficient at room temperature, but at high temperatures, it is contrary.

In a previous work, we studied the mechanical properties and thermal stability of nanostructured Al/ $\text{Al}_{12}(\text{Fe,V})_3\text{Si}$ alloys [14]. The aim of the present study was to investigate the tribological properties of nanostructured Al/ $\text{Al}_{12}(\text{Fe,V})_3\text{Si}$ alloys. In this regard, a nanostructured pure Al and two nanostructured Al/ $\text{Al}_{12}(\text{Fe,V})_3\text{Si}$ alloys containing 27 and 37 vol% of $\text{Al}_{12}(\text{Fe,V})_3\text{Si}$ precipitates were produced by MA and subsequent HP of elemental powders. Then, their wear behavior was studied under dry sliding condition, and the effect of $\text{Al}_{12}(\text{Fe,V})_3\text{Si}$ volume fraction on the wear performance was discussed.

2 Experimental

The materials used in this study were fabricated by MA followed by HP. The elemental powders with the compositions given in Table 1 were used as starting materials. MA was carried out in a planetary ball mill at room temperature under argon atmosphere for 60 h. A ball to powder mass ratio of 10:1 and a rotation speed of 500 r/min were employed. The milled powders were then underwent uniaxial HP at 550 °C under a pressure of 300 MPa for 20 min to prepare disk samples of $\Phi 50 \text{ mm} \times 15 \text{ mm}$. The Archimedes technique was used to measure the densities of the hot-pressed samples. Hardness test was conducted with

Fig. 1 XRD patterns of hot-pressed samples

Vickers indenter at a load of 10 kg. In order to study the phase composition of the produced alloys, XRD patterns of the hot-pressed samples were recorded in a Philips X PERT MPD diffractometer using filtered $\text{CuK}\alpha$ radiation. The grain size and internal strain of the samples were evaluated based on the XRD line broadening using the Williamson–Hall equation [15].

Friction and wear properties of the samples were investigated by a pin-on-disk wear test machine according to the ASTM G99-05 standard, where AISI 52100 steel with the hardness of 63 RC and an average R_a value of 0.4 μm was used as the pin. The disk samples were machined and then polished to the 2,400 grid polish before the wear test. The tests were conducted at room temperature and a relative humidity of 40% under an unlubricated condition. The sliding speed was 0.12 m/s and the applied normal loads were 2, 5, and 10 N for all tests. The mass losses of the disks were measured at different time intervals in sliding distance with an analytical balance of 0.1 mg. The total sliding distance was 500 m. The weight loss of pin after test was also measured with the 0.1 mg precision. The friction coefficients were continuously recorded with the sliding distance. The worn surfaces and wear debris were examined by a Philips XL30 scanning electron microscope (SEM) with an energy dispersive X-ray spectrometer (EDS) attachment.

3 Results and Discussion

3.1 Characteristics of Hot-pressed Samples

Figure 1 shows the XRD patterns of hot-pressed samples. The peaks of $\text{Al}_{12}(\text{Fe,V})_3\text{Si}$ and Al were observed in the XRD patterns of FVS0812 and FVS1212 samples. For the pure Al sample, only Al peaks were present.

Table 2 Characteristics of as-pressed specimens

Sample	Grain size (nm)	Internal strain (%)	Relative density (%)	Hardness (HV)
Al	70	0.26	99.5	76
FVS0812	54	0.4	97	205
FVS1212	50	0.38	97	254

The characteristics of hot-pressed samples are presented in Table 2. FVS0812 and FVS1212 samples had significantly higher hardness values than the pure nanostructured Al due to the presence of $\text{Al}_{12}(\text{Fe,V})_3\text{Si}$ precipitates. The hot-pressed samples exhibited high relative densities over 97%. The grain sizes of the samples were between 50 and 70 nm with relatively high levels of internal strain.

3.2 Wear Performance

3.2.1 Wear Rate

The wear mass losses of the samples versus sliding distance are shown in Fig. 2. In all samples, the weight loss continuously increased with increasing the sliding distance, but the rate of mass loss decreased at higher sliding distances. The initial high rate of mass loss is due to the run-in period in the early stage of test [16]. The wear rate of the samples as a function of the applied normal load is graphically presented in Fig. 3. According to this figure, the wear rate progressively increases with the applied load. Moreover, the wear rate decreases as the fraction of $\text{Al}_{12}(\text{Fe,V})_3\text{Si}$ precipitates increases from 0 to 37 vol% in all loads. The lowest wear rate was obtained for the FVS1212 sample at 2 N applied normal load and the highest wear rate was for the nanostructured pure Al at 10 N. The improvement of the wear resistance with increasing the precipitates content can be owned to the effective load transfer from the Al matrix to the hard precipitates and hence less material removal in comparison with the nanostructured pure Al sample. It was reported in numerous studies that the wear rate reduces with increasing

Fig. 3 Variation of the wear rate as a function of normal load for different samples

the reinforcement content. Mohammad Sharifi and Karimzadeh [1] observed a reduction in the wear rate of $\text{Al}/\text{Al}_2\text{O}_3\text{--AlB}_{12}$ hybrid composite with increasing the $\text{Al}_2\text{O}_3\text{--AlB}_{12}$ weight fraction from 5 to 15 wt%. A similar trend was reported by Sulima *et al.* [17] for the wear rate of AISI 316L stainless steel composites reinforced with 2, 4, 6, and 8 vol% of titanium diboride (TiB_2) particles.

3.2.2 Characterization of Worn Surfaces

To find the wear mechanism of the samples, the worn surfaces were investigated by SEM and EDS. SEM image of the worn surface of nanostructured Al sample at 5 N applied normal load with the SEM image and EDS analysis of the wear debris of this sample is presented in Fig. 4. Effect of delamination was observed on the worn surface. The wear debris were large and most of them had stratified morphology which is a characteristic of adhesive wear [18]. This kind of morphology was previously observed for the wear debris of pure coarse-grained Al [19]. These observations suggest that adhesive wear is the dominant wear mechanism for the nanostructured Al sample at 5 N

Fig. 2 Wear mass loss as a function of sliding distance for different samples at applied loads: **a** 2 N, **b** 5 N, **c** 10 N

Fig. 4 **a** SEM image of the worn surface of nanostructured Al sample at 5 N applied normal load, **b** SEM image and **c** EDS analysis of the wear debris

applied normal load, which is consistent with the high mass loss observed for the pure Al sample at this load. EDS analysis results of the wear debris only showed the peak of Al, indicating that material transfer from the steel pin was not occurred during the sliding. It is worth mentioning that at the applied normal load of 10 N, surface damage of the pure Al sample was so severe that it was not possible to find a wear mechanism.

SEM images of the worn surfaces of FVS0812 and FVS1212 samples at various applied normal loads are shown in Fig. 5. It is observed that the surface damage increases with increasing the applied normal load. Moreover, the wear mechanism changes with changing the normal load.

As shown in Fig. 5a, deep scratches and small grooves were observed on the worn surface of FVS0812 sample at the normal load of 2 N, indicating that abrasive wear is the dominant wear mechanism. On the worn surface of FVS1212 sample at the same load (Fig. 5b), only shallow scratches were seen, indicating that the governing mechanism for this sample is also the abrasive wear. The lower surface damage of FVS1212 sample is consistent with the wear rate results shown in Fig. 3. The following equation has been proposed for the abrasive wear of ductile materials [20]:

$$V = \alpha\beta \frac{WL}{H_V}, \quad (1)$$

where V is the wear volume, W the normal load, L the sliding distance, α the shape factor of an asperity, β the degree of the wear by abrasive asperity, and H_V is the Vickers hardness. According to this equation, the wear volume is inversely related to the hardness. In fact, material loss under abrasive wear condition takes place by plowing. This mechanism needs the penetration of hard asperities of

the steel pin into the counterface, which is controlled by the hardness of counterface material. Therefore, hardness has a significant effect on the abrasive wear resistance. As observed in Table 2, FVS1212 sample has higher hardness value than FVS0812 sample because of the higher volume fraction of strengthening precipitates. Therefore, according to Eq. (1), FVS1212 sample is expected to be more resistant to abrasive wear than FVS0812, which is consistent with the observed wear weight losses and SEM results.

On the worn surface of FVS0812 sample at 5 N applied normal load, effects of material flow and grooves were observed. These features indicate that the wear mechanism is changed from abrasive to adhesive at this load. For FVS1212 sample, only the scratches slightly deepened and the grooves slightly severed compared with the worn surface at 2 N applied load, suggesting that the wear mechanism is still abrasive but the material removal intensified owing to the higher applied normal load.

At the load of 10 N, the worn surfaces of both the samples exhibited different appearance compared with those observed for 2 and 5 N loads. Effect of delamination was observed on the worn surfaces at this load. The worn surfaces were divided into two distinct regions: one region with a very low surface damage and the other with heavy material flow and sever wear, indicating the local adhesion between the specimen surface and the counter body. Low magnification SEM images of the wear tracks of samples at 10 N normal load in back-scattered mode are shown in Fig. 6. The wear track was covered by a darker layer in some regions. The SEM micrograph suggests that the darker layer should have a different chemical composition from the other surface regions.

Higher magnification SEM images with the corresponding EDS analysis of the dark layer (marked as A) and bright area (marked as B) on the worn surfaces of FVS0812

Fig. 5 SEM micrographs of the worn surfaces of FVS0812 **a, c, e**; FVS1212 **b, d, f** samples at different applied normal loads: **a, b** 2 N; **c, d** 5 N; **e, f** 10 N

Fig. 6 Low magnification SEM image in back-scattered mode showing the wear track at 10 N normal load: **a** FVS0812, **b** FVS1212

Fig. 7 High magnification SEM image of the *dark* and *bright* area on the wear track of FVS0812 sample with the EDS analysis of corresponding areas

and FVS1212 samples are shown in Figs. 7 and 8. The SEM images show that the darker layer was relatively smooth with some narrow scratches and microcracks, whereas the bright area had more surface damages with the effects of material flow, indicating the adhesion between the sample and the pin body. EDS analysis results of the darker layer showed that this layer has higher Fe and O content than the bright area. The presence of the higher amount of Fe in the darker layer implies the transfer of Fe from the steel pin to the worn surface, while the presence of O is probably due to the oxidation reaction. These results indicate that a mechanically mixed layer (MML) has been formed on the worn surfaces. It seems that formation and delamination of a MML is a governed wear mechanism at 10 N applied normal load for both the samples.

Venkataraman and Sundararajan [21] observed the formation of MML on the worn surfaces of Al7075 alloy and Al-SiC composite. Formation of MML on the worn surface was also reported for many other Al alloys and composites such as Al-Si [22], Al8090 and Al8090-SiC [23], and Al6061 and Al-Mg-Si-CoNi [24]. Some characteristics of the MML are as follows [25]: it has a darker color than other regions of the surface; it contains chemical elements

Fig. 8 High magnification SEM image of the *dark* and *bright* area on the wear track of FVS1212 sample with the EDS analysis of corresponding areas

like Fe coming from the counter body and has higher hardness value than outside the MML. In the case of Al alloys and composites sliding against a steel counter body, MML also contains oxides of Al and Fe. Because MML has a higher hardness than the alloy or composite and consists of oxides with the low friction coefficient, it acts as a protecting layer to the surface [25, 26]. This is the reason for the lower surface damages in the dark regions in Figs. 7 and 8. It should be mentioned that MML is not formed on the worn surface of unreinforced pure Al [1]. EDS analysis of the wear debris of pure nanostructured Al sample (Fig. 4) also showed the peak of Al element without the trace of any other element.

Figure 9a represents the weight losses of steel pins after wear test at different normal loads. It is observed that the weight losses of pins significantly increase with increasing the normal load. This is because at low loads, the contact shear stress was not sufficient to detach material from the pin, but at high loads, the shear stress surpassed the yield strength of the steel pin, and therefore individual fragments were detached from the pin surface and deformed under the

Fig. 9 **a** Weight loss of the steel pin after wear test at different loads, **b** atomic percentage of Fe in worn surface of alloys at different loads

pressure of pin. Figure 9b shows the atomic percentage of Fe in the worn surfaces of the samples as a function of the applied normal load obtained by EDS analysis. According to this figure, atomic percentage of Fe on the worn surfaces increases with increasing the normal load. At low loads, the amount of Fe on the worn surfaces was very close to its initial value in the alloy composition. Li and Tandon [22] also reported that the mass percentage of Fe in the wear debris of Al–Si alloy and Al–SiC composite sliding against the steel increases with an increase in the normal load. Considering the weight loss of pin and EDS analysis results, it can be concluded that at 2 and 5 N normal loads, the amount of Fe transferred from the steel pin to the worn surface was not sufficient to form a consistent layer on the wear track, and therefore MML was not formed. However, as the normal load increased to 10 N, the amount of Fe detached from the steel pin increased, and the MML was formed. According to Fig. 9b, larger amount of Fe was present on the worn surface of FVS1212 sample compared with that on the worn surface of FVS0812 at all loads, probably because of the higher atomic percentage of Fe in its original composition or higher Fe removal from the steel pin. It should be mentioned that the pin sliding against the FVS1212 sample showed higher weight loss, which may be due to the higher hardness value of this sample as a result of higher precipitate content. It has been shown in numerous studies that increasing the reinforcement content in the material promotes stronger material transfer from the counterface and faster formation of MML [22, 27, 28].

3.2.3 Wear Debris

In order to understand the wear behavior further, the wear debris of FVS0812 and FVS1212 samples were also studied using SEM. Figure 10 shows the SEM images of the wear products of FVS0812 and FVS1212 samples generated under different loads. The size of the debris increased with increasing the normal load. Moreover, the wear debris

of FVS1212 sample had smaller size than those of FVS0812 sample in all normal loads.

At the applied normal load of 2 N, the wear debris was mostly in the form of fine particles. The diameter of most of the particles was less than 5 μm , indicating a low surface damage. In fact, these fine particles were removed from the grooves and scratches observed in Fig. 5a and b.

At the normal load of 5 N, most of the wear debris of FVS0812 sample had stratified morphology, while some fine particles were still observed. The presence of the debris with the stratified morphology was an indication of the adhesion mechanism [18]. However, abrasive wear had also led to the formation of fine particles at this load. Therefore, it can be concluded that the dominant wear mechanism for FVS0812 sample at this load is the adhesive wear. For the FVS1212 sample, wear debris were still in the form of fine particles and flakes similar to those observed at 2 N normal load, but with larger sizes. Therefore, abrasive wear is again the dominant mechanism of wear for this sample. The larger wear debris at this load was due to the higher load which leads to the deepening of scratches and grooves and therefore enhanced material removal from the surface.

The wear debris of FVS0812 sample at 10 N normal load showed two different shapes: stratified morphology which can be attributed to an adhesive mechanism and plate shape which suggests delamination. It seems that the MML was first detached by the delamination mechanism, and then the stratified particles were removed progressively by the adhesion mechanism. For the FVS1212 sample at this load, the wear debris were a combination of fine particles and plate shape debris. Smaller size of the plate shape debris for the FVS1212 sample compared with those for the FVS0812 sample at this load indicates that the MML formed on the wear track of FVS1212 sample was more resistant to the delamination than that for FVS0812. Furthermore, it seems that after the MML was delaminated, the worn surface of FVS1212 sample had experienced less

Fig. 10 SEM micrographs of the wear debris of FVS0812 **a, c, e**; FVS1212 **b, d, f** samples at different normal loads: **a, b** 2 N; **c, d** 5 N; **e, f** 10 N

damage than the worn surface of FVS0812 sample owing to its higher hardness. These results are in line with the wear rate results.

In order to confirm the delamination of MML from the worn surfaces of FVS0812 and FVS1212 samples at 10 N normal load, the EDS analysis was conducted on the wear products obtained at this load. Figure 11 illustrates the EDS analysis of the wear products of FVS0812 and FVS1212 samples generated under 10 N normal load. It is observed that the wear debris of both the samples contain more Fe than the initial composition of the alloy. Further, an amount of O was detected in the chemical composition of debris. The presence of Fe and O in the chemical

composition of debris confirms that most of the wear debris was formed by the delamination of MML.

As observed, the Al–Fe–V–Si alloys studied here show different wear mechanisms at different applied normal loads. Al alloys are known to exhibit two types of wear behavior: mild and severe [29]. A transition from mild wear to severe wear occurs with increasing the normal load. Severe wear involves massive surface damage and material transfer from the counterface [30]. It has been shown that the removal of MML is responsible for the severe wear at high applied loads [31]. The SEM images in Figs. 7 and 8 also exhibited severe surface damages in the areas where MML was detached.

3.2.4 Friction Coefficient

Figure 12 shows the variation of the coefficient of friction (COF) of the samples as a function of the sliding distance at different applied normal loads. A comparison between graphs demonstrated that the FVS1212 sample, which contains 37 vol% of the $\text{Al}_{12}(\text{Fe,V})_3\text{Si}$ precipitates, has the lowest COF at all loads, whereas the nanocrystalline Al

sample has the highest value. The lower COF of FVS1212 sample can be attributed to the higher hardness value of this sample, which is in line with the previous reports of decrease in COF with increase in hardness [32], and is also in line with the wear rate results shown in Fig. 3. Based on the above, the presence of $\text{Al}_{12}(\text{Fe,V})_3\text{Si}$ precipitates reduces the COF of Al alloys. It is worth mentioning that the COF changed slightly with changing the applied load probably because of the changes in wear mechanism.

The friction coefficients obtained here for the nanocrystalline Al/ $\text{Al}_{12}(\text{Fe,V})_3\text{Si}$ alloys (0.3–0.5) are in the range of those reported in the literature for nanostructured Al alloys and composites. Jafari *et al.* [9] observed a COF of 0.3 for nanostructured Al2024 alloy. Mohammad Sharifi *et al.* [1] reported a COF of 0.3–0.4 for steady state friction coefficient of Al– B_4C nanocomposites containing (5–15) wt% of B_4C particles.

4 Conclusions

- (1) The wear weight loss of the alloys increased with the sliding distance and applied normal load.
- (2) The wear resistance of the alloys increased with increasing the $\text{Al}_{12}(\text{Fe,V})_3\text{Si}$ content. The wear rate of

Fig. 11 EDS analysis of the wear products of FVS0812 **a**; FVS1212 **b** samples, generated under 10 N normal load

Fig. 12 Variations of COF of Al **a, b, c**, FVS0812 **d, e, f**, FVS1212 **g, h, i** samples as a function of sliding distance (SD): **a, d, g** 2 N; **b, e, h** 5 N; **c, f, i** 10 N

nanostructured pure Al, FVS0812, and FVS1212 alloys varied between 0.02 and 0.072, 0.012 and 0.0514, and 0.0064 and 0.0316 mg/m for studied loads, respectively.

- (3) The wear mechanism of nanostructured FVS0812 and FVS1212 alloys changed with the applied normal load. For the nanostructured FVS0812 alloy the dominant wear mechanism was abrasion and adhesion at 2 and 5 N normal loads, respectively, whereas for the nanostructured FVS1212, the dominant wear mechanism was abrasion at the same loads.
- (4) A mechanically mixed layer (MML) was formed on the worn surface of both the nanostructured FVS0812 and FVS1212 alloys at the normal load of 10 N. EDS analysis showed that this layer contains an amount of Fe and O. Formation and delamination of the MML controls the wear behavior of nanostructured FVS0812 and FVS1212 alloys at 10 N normal load.
- (5) The friction coefficient decreased with increasing the $\text{Al}_{12}(\text{Fe,V})_3\text{Si}$ content. The average value of friction coefficient for the nanostructured pure Al, FVS0812, and FVS1212 alloys varied between 0.6 and 0.8, 0.4 and 0.5, and 0.3 and 0.4, respectively.

References

- [1] E. Mohammad Sharifi, F. Karimzadeh, *Wear* **271**, 1072 (2011)
- [2] K. Kaur, R. Anant, O.P. Pandey, *Tribol. Lett.* **44**, 41 (2011)
- [3] A. Vencel, I. Bobić, M. Jovanović, M. Babić, S. Mitrović, *Tribol. Lett.* **32**, 159 (2008)
- [4] M. Nofar, H.R.M. Hosseini, N. Kolagar-Daroonkolaie, *Mater. Des.* **30**, 280 (2009)
- [5] M. Alipour, B.G. Aghdam, H.E. Rahnoma, M. Emamy, *Mater. Des.* **46**, 775 (2013)
- [6] A. Mahboubi Soufiani, F. Karimzadeh, M.H. Enayati, *Mater. Des.* **37**, 152 (2012)
- [7] N. Hosseini, F. Karimzadeh, M.H. Abbasi, M.H. Enayati, *Tribol. Int.* **54**, 58 (2012)
- [8] P. Salehikahrizangi, F. Karimzadeh, M.H. Enayati, M.H. Abbasi, *Wear* **305**, 51 (2013)
- [9] M. Jafari, M.H. Enayati, M.H. Abbasi, F. Karimzadeh, *Mater. Des.* **31**, 663 (2010)
- [10] S. Das, in *Intermetallic Compounds*, ed. by J. Westbrook and R.L. Fleischer, (Wiley & Sons Ltd, New York, 1994), p. 175
- [11] S. Lee, D.Y. Lee, N.J. Kim, *Mater. Sci. Eng. A* **147**, 33 (1991)
- [12] D.J. Skinner, R.L. Bye, D. Raybould, A.M. Brown, *Scr. Mater.* **20**, 867 (1986)
- [13] C.C. Yang, W.M. Hsu, E. Chang, *Mater. Sci. Technol.* **13**, 687 (1997)
- [14] H. Ashrafi, M.H. Enayati, R. Emadi, *J. Mater. Eng. Perform.* **23**, 1780 (2014)
- [15] G.K. Williamson, W.H. Hall, *Acta Metall.* **1**, 22 (1953)
- [16] A.M. Hassan, A.T. Mayyas, A. Alrashdan, M.T. Hayajneh, *J. Mater. Sci.* **43**, 5368 (2008)
- [17] I. Sulima, P. Klimczyk, P. Malczewski, *Acta Metall. Sin. (Engl. Lett.)* **27**, 12 (2014)
- [18] G. Stachowiak, A.W. Batchelor, *Engineering Tribology* (Waltham, Oxford, 2004), pp. 542–544
- [19] A. Alizadeh, E. Taheri-Nassaj, *Mater. Charact.* **67**, 119 (2012)
- [20] K. Kato, in *Wear-materials, Mechanisms and Practice*, ed. by G.W. Stachowiak (Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, 2006), p. 9
- [21] B. Venkataraman, G. Sundararajan, *Wear* **245**, 22 (2000)
- [22] X.Y. Li, K.N. Tandon, *Wear* **245**, 148 (2000)
- [23] J. Rodriguez, P. Poza, M.A. Garrido, A. Rico, *Wear* **262**, 292 (2007)
- [24] H.J. Kima, J.M. Lee, Y.H. Cho, S.Y. Sung, B.S. Han, Y.S. Ahn, *Mater. Charact.* **70**, 137 (2012)
- [25] M.R. Rosenberger, C.E. Schvezov, E. Forlerer, *Wear* **259**, 590 (2005)
- [26] M.J. Ghazalia, W.M. Rainforthb, M.Z. Omar, *J. Mater. Process. Technol.* **201**, 662 (2008)
- [27] D. Lu, M. Gu, Z. Shi, *Tribol. Lett.* **6**, 57 (1999)
- [28] R.N. Rao, S. Das, *Mater. Des.* **31**, 1200 (2010)
- [29] J.F. Archard, W. Hirst, *Proc. R Soc. A* **236**, 397 (1956)
- [30] K.C. Ludema, *Wear* **100**, 315 (1984)
- [31] B. Venkataraman, G. Sundararajan, *Acta Mater.* **44**, 461 (1996)
- [32] A.S. Anasyida, A.R. Daud, M.J. Ghazali, *Mater. Des.* **31**, 365 (2010)