Composite Interfaces

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tcoi20

Tribological properties of Al7075-SiC nanocomposite prepared by hot dynamic compaction

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Published online: 22 Jun 2015.

To cite this article: G.H. Majzoobi, A. Atrian & M.H. Enayati (2015) Tribological properties of Al7075-SiC nanocomposite prepared by hot dynamic compaction, Composite Interfaces, 22:7, 579-593, DOI: 10.1080/09276440.2015.1055955

To link to this article: http://dx.doi.org/10.1080/09276440.2015.1055955

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Tribological properties of Al7075-SiC nanocomposite prepared by hot dynamic compaction

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(Received 6 May 2015; accepted 26 May 2015)

Wear resistance of Al7075-SiC nanocomposite prepared by hot dynamic compaction was investigated in this article. Mechanically milled micro-sized Al7075 with different amounts of SiC nanoparticles (SiCnp), 0, 5, and 10 vol%, were used to fabricate the samples. Dynamic compaction was conducted at the strain rates of about $10^3$ s$^{-1}$. A mechanical drop hammer was used to fabricate the nanocomposite samples with relative density of up to 98%. The microstructural and mechanical behaviors of the samples, such as microhardness and stress–strain curves, were also investigated. The results showed improvement in microhardness and compressive strength of the material. The improvement is believed to be mainly due to the Orowan mechanism rather than the grain refinement described by the Hall–Petch effect. The results also revealed reduction in wear resistance as SiC reinforcing particles increased. The microstructural study of the eroded surfaces indicated that the abrasive and delamination were the dominant wear mechanisms.

Keywords: SiC; composite; powder; dynamic compaction; wear

1. Introduction

Aluminum matrix composites (AMC) are widely used in aerospace, automotive, military and microelectronics industries because of their superior properties such as wear resistance and strength-to-weight ratio.[1] Since the use of aluminum alloys is often restricted by their poor wear resistance, there is a great interest in production of AMC particularly for tribological applications in different vehicles components.[2,3] By reinforcing such alloys with ceramic nanoparticles such as SiC, Al2O3, B4C, and TiB2 through powder metallurgy (PM), aluminum matrix nanocomposites (AMNC) can be produced with higher mechanical properties. Among the aluminum alloys, Al7075 has gained more applications over the past decades. This is due to its mechanical properties which are comparable with some of steel alloys.[4] Improvement of wear resistance of ceramic micro- or nanoparticles reinforced aluminum alloys has been investigated by some researchers in recent years.[1–3,5–7]

Different PM techniques based on thermo-mechanical processes can be used for preparation of particulate reinforced nanocomposites. In all of these techniques, the load can be applied either quasi-statically or dynamically. Hot pressing,[8] hot isostatic...
pressing [9] and hot extrusion [10] are typical examples of quasi-static loading. As stated above, the composites can also be produced under dynamic compaction [11,12] or shock wave consolidation.[13] These techniques usually use dropping hammer, explosives or compressed gas as the propellant to accelerate a projectile for compaction. The main advantage of these types of production techniques is that hot sintering is usually (but not always) eliminated from the production cycle. Such techniques offer the possibility of producing the high temperatures necessary for adequate local metallurgical bonding at the powder particle interfaces, precisely where it is required, while the powder remains relatively cool elsewhere. Therefore, the microstructural changes such as particles agglomeration and grains growth, which may happen due to high temperature rise, can be minimized.[14]

Some researchers such as Wang et al. [11] and Yan et al. [15] used dynamic devices for compaction purposes. Atrian et al. [12] compared dynamic compaction and hot pressing techniques in processing and characterization of Al7075-SiC nanocomposite. Khan et al. [16] also conducted high velocity for compaction of Ti-6Al-4 V powder. The compacted samples were then sintered, examined by scanning electron microscopy (SEM), and their microhardness and bending strength were measured. Some researchers also studied tribological behavior of different PM samples. Jafari et al. [17] investigated wear mechanisms of nanostructured Al2024 alloy. Hosseini et al. [3] studied tribological behavior of Al6061-Al2O3 nanocomposites fabricated by hot pressing. Their results indicated that wear rate increases with the increase of the reinforcing particle size. Wang et al. [18] also investigated the effects of surface nanocrystallization on tribological properties of 316L stainless steel.

In the current work, Al7075-SiC nanocomposite is fabricated by mechanical milling and hot dynamic compaction. The main objective of this study was to explore the aspects of nanoparticles reinforced Al7075. Moreover, the effect of volume fraction of nano reinforcement on density, compressive behavior, microhardness, wear resistance and microstructural behavior of the specimens is investigated. Study of the tribological behavior and the wear mechanisms in dynamically compacted AMNC samples is also investigated.

2. Experiments

2.1. Materials

The matrix is Al7075 powder prepared by water atomization technique, with the average size of 100 μm and irregular morphology, and the reinforcing particle is SiC nanoparticles (SiC_{np}) with average size of 50 nm, purity > 99.0%, specific surface area > 90 m²/g, and nearly spherical morphology.

2.2. Mechanical milling

The matrix and reinforcing powders were mixed together to produce Al7075-5 vol% SiC and Al7075-10 vol% SiC nanocomposite powders. In order to obtain a homogeneous dispersion of nanoparticles in the matrix, the mixed powders were poured in ethanol and then the solution was subjected to ultrasonic vibration for 30 min. After drying, the mixture was milled in a planetary ball mill at room temperature and in the inert argon atmosphere. The milling media included twenty-two hardened chromium steel balls with a diameter of 10 mm confined in a 125-ml hardened chromium steel vial. The milling rotational speed and the milling duration were 300 rpm and 2 h.
respectively. Since ductile metal powders such as aluminum are prone to adhesion to milling balls during the milling process, about 0.5 wt% stearic acid as process control agent was added to the mixture to reduce the effect of unwanted adhesion.[19] The number and total weight of the steel balls were also selected in a way to get more collisions between the balls and the powders and to achieve a ball-to-powder mass ratio of 3:1.

2.3. Hot dynamic compaction

In order to fabricate the nanocomposite samples about 5 g of the milled powder were uniaxially compacted under dynamic loading. The die assembly including the 1.2344 heat-treated hot-worked steel die and a 1.2542 shock-resisting steel punch with 15 mm diameter was used for powder compaction. Two 5 mm thick tablets made of the punch material and with the same diameter were placed beneath and on the top of the powder. This was to facilitate the compacted specimens to be pulled out from the die, to reduce the spring-back effect of the specimen and finally, to improve the compaction quality and properties.[20] High-temperature MoS2 was used as the lubricant to minimize the frictional forces between the die wall and to improve the surface quality of the samples. The temperature for dynamic compaction was kept constant at about 698 K using a 1200 W ceramic heating element. The compacted sample had cylindrical shape with 8 mm length and 15 mm diameter.

A mechanical drop hammer with 60 kg falling weight was employed to create the required energy for compaction (Figure 1). The impact velocity \( V \) of the weight for a falling height of 3.5 m was computed as 8 m/s \( (V = \sqrt{2gh}) \). This impact velocity produces about 2 kJ energy \( (E = mV^2/2) \) which is delivered to the powder for compaction. Since the punch is lighter than the dropping weight, its velocity, based on the principle of conservation of momentum, is obviously more than 8 m/s.[21] In order to transfer the whole impact energy to the powder, the assembly of the compaction die was fixed to the ground. The application of a 73 kg force revealed that any load in excess of 60 kg will lead to cracking and damaging of the samples.

2.4. Characterization

In order to investigate the structural changes which may occur during milling and compaction process and also to measure the grain size, the X-ray diffraction (XRD) patterns of the samples were recorded using a PHILIPS X’PERT PW3040 diffractometer (40 kV/30 mA) with CuKα radiation (\( \lambda = 0.154059 \) nm). The Vickers microhardness of the samples was measured by applying a 100 g force to the specimen for 15 s using a tetragonal indenter. Compressive behavior of the samples was also studied using a 60 tons Instron testing machine under strain rate of about 0.008 s\(^{-1}\). Density, as an important factor to qualify the consolidation of powder materials, was measured using the Archimedes principle.

A pin-on-disk wear test which is illustrated schematically in Figure 2 was also used to evaluate tribological behavior of the nanocomposite samples. All wear tests were conducted for a total sliding distance of 500 m and the sliding speed of 0.08 m/s. The hot dynamically compacted samples with 15 mm diameter were placed in a 30-mm diameter disk-shape container. This is to fix the samples to the tribometer during the wear test. Before conducting the wear test, the specimen surface was cleaned by ethanol and then was dried. Pins made from AISI 52,100 carbon steel with the hardness of
63 Rc were used as the counter faces. The wear tests were performed by applying a constant 10 N axial load to one end of the pin, while the other end of the pin was allowed to slide against the disk in a dry friction condition.

3. Results and discussion

3.1. Microstructural characterization

Figure 3 shows the morphology of the nanocomposite powder after mechanical milling. The figure reveals that the SiC\textsubscript{np} have fully covered the surface of Al7075 micrometer
size particles after 2-h mechanical milling. The XRD patterns of nanocomposite powder with different amounts of nanophase reinforcement shown in Figure 4 indicates that the milled powder included only Al and SiC and no new phase (such as Al4C3) was produced as a result of milling. These may be attributed to short duration of milling. Williamson-Hall analysis [12] also showed that when SiC content increases, the crystallite size of Al7075 matrix increases in both of the nanocomposite milled powder and the hot dynamically compacted samples. This behavior can be explained by SiC effects on milling efficiency.[12]

3.2. Physical and mechanical characterization

Volume fraction of hard phase particles in a multi-phases microstructure is the most important factor affecting density and mechanical properties such as strength and fracture toughness.[22] Figure 5 illustrates the variation of relative density vs. SiC vol%.

Figure 3. FESEM micrograph of Al7075-5 vol% SiCnp after 2 h of ball milling.

Figure 4. XRD pattern of 2 h ball-milled of (a) Al7075, (b) Al7075-5 vol% SiCnp, (c) Al7075-10 vol% SiCnp.
As the figure suggests, the relative density of the specimens reduces as the SiC content increases from 0 to 10 vol%. The hard and non-deformable particles dispersed in a ductile matrix particles gives rise to reduction of the compactability of the powder. Agglomeration of nanoparticles can also be another reason for low densification seen in Figure 6. Razavi-Tousi et al. [22], Dong et al. [23], and Rahimnejad Yazdi et al. [24] also reported that the relative density reduces with the increase of volume fraction of reinforcing particles. They mainly attributed this behavior to deformation intensity of the matrix material in the vicinity of reinforcing particles. They also believed that blocking the grain boundary movement and hindering of the densification of matrix material caused by reinforcing particles could be other reasons for density reduction.

Variation of Vickers microhardness and compressive behavior of dynamically compacted specimens vs. SiC volume fraction are illustrated in Figures 7 and 8, respectively. As the figures suggest, SiC reinforcement could increase microhardness and strength of the compacted samples by around 20 and 60%, respectively. In fact, despite reduction of density with the increase of SiC content, the nano reinforcement could enhance the hardness due to its hardening effects and its intrinsic hardness. Alizadeh and Taheri-Nassaj [10], Dong et al. [23], and Canakci [6] also reported similar observations in their investigation. The improvement of hardness is related to the material strength enhancement. The results shown in Figures 7 and 8 agree approximately well with Tabor equation [25] in which the yield strength ($\sigma_y$) and hardness ($HV$) are related to each other as follows:

$$\sigma_y = HV/3$$

As stated before, Williamson-Hall [26] analysis showed grain coarsening for compacted samples for higher SiC contents. Therefore, the strength improvement cannot be explained by the Hall–Petch effect [26] which assumes that strengthening is due to dislocation pile-up at the grain boundaries. As a result, the strengthening may be explained by the Orowan mechanism [12,27] in which SiC dispersion become barrier to dislocation movement and improving the strength of material. Similar results were also reported by Kollo et al. [19] who used hot pressing to fabricate Al-SiC nanocomposite.

![Figure 5. Variations of relative densities vs. SiC content.](image-url)
3.3 Wear properties

Variation of weight loss vs. sliding distance for dynamically compacted specimens is illustrated in Figure 9. The figure indicates that unlike the improving effects of the second phase reinforcement on the compressive behavior and microhardness of the dynamically compacted specimens, the wear resistance is reduced as SiC content increases. Variation of wear rate vs. the SiC content is depicted in Figure 10. As the figure shows, for the 10 N applied load and 500 m distance, the wear rate of the compacted samples increases from about 0.2 to 1.4 mg/m when the SiC content increases.
Figure 8. True stress–strain behavior of hot dynamically compacted samples.

Figure 9. Variation of weight loss vs. sliding distance in nanocomposite samples.

Figure 10. The effect of SiC volume percentage on the wear rate.
from 0 to 10%. This does not agree with the results reported by the researchers who have used different powder compaction techniques under quasi-static loading. Mohammad Sharifi et al. [5] reported improvement for wear resistance of Al-B4C nanocomposites as B4C content increased. They used hot pressing for fabrication of the nanocomposite samples. Abdollahi et al. [7] also reported similar results for Al2024-B4C nanocomposite samples fabricated by mechanical milling and hot extrusion. The wear behavior in this study does not comply with Archard equation [3] in which the wear rate is inversely proportional to hardness. This type of behavior can be attributed to weak bonding between Al7075 and SiC particles during dynamic consolidation. The governing wear mechanism on nanocomposite samples was evaluated using SEM micrographs of the worn surfaces with energy dispersive spectroscopy (EDS) analyses.

Typically, SEM micrographs of the worn surfaces of dynamically compacted samples having different SiC contents are illustrated in Figures 11 and 12. Evidences of delamination and deep craters on the worn surface can be observed in Figure 11. This implies that delamination can be one of the wear mechanisms.[17] Since there is no noticeable metal flow on the surface where only some craters are observable, mild adhesive can be another wear mechanism.[1,28] Kumar et al. [1] considered the adhesion as the dominating wear mechanism in Al-7Si/TiB2 composite in which heavy metal flow had occurred during sliding.

The narrow and parallel grooves visible in Figure 11(a) and with higher magnification in Figure 11(b) show that abrasion can also be a dominant wear mechanism [3,5,17]. This can be attributed to the presence of hard SiCnp which restrict material flow during sliding.[3] Canakci [6] also reported abrasive wear mechanism for Al2014-B4C composite fabricated by stircasting method. EDS point analysis presented in Figure 11(c) also shows Fe and Cr in the worn surface. These elements which are transferred from the steel pin to the worn surface are another signs of abrasive wear mechanism.

Weak bonding of Al7075 and SiC particles in dynamic compaction is thought to be the main reason for reduction of wear resistance. During the impact, the peak pressure is applied instantly, and therefore, the powder particles do not have enough time to be exposed to pressure and temperature simultaneously. As a result, full sintering does not occur and Al and hard SiCnp detach from the surface by the steel pin during the wear test. These hard particles act as abrasive agent and produce most of the narrow grooves illustrated in Figure 11(b). Under such condition, the effective load transferred from the matrix to the hard ceramic particles is reduced, and therefore, the wear rate increases as SiC fraction increases.[17] It is obvious that the detrimental effect of SiCnp and surfaces erosion is more serious for samples having higher values of nano reinforcement (Figure 12). Moreover, due to inhomogeneous dispersion of SiCnp, the worn surface is also not homogeneous as seen in Figure 12. On the other hand, the dispersion of nano-phase during material flow can produce dislocation pile-up around inclusions in the matrix material. The dislocation pile-up presumably leads to initiation and propagation of cracks at the sub-surfaces. This causes material loss from the worn surface in the shape of flakes.[3] The flake-shape wear debris of each sample is presented in Figure 13. The microcracks and delamination seen in the flakes verify that governing wear mechanism can be the delamination. It is obvious in Figure 13 that as SiC content increases, the size of wear debris reduces. The smaller size of debris shows the abrasive role of hard nanoparticles. As a result, in the samples with higher nanoparticle contents, more and smaller debris are produced. Consequently, it can be said that in samples with finer wear debris, the effects of abrasive mechanism are more remarkable.[17]
Figure 11. SEM micrograph of worn surface of hot dynamically compacted Al7075-10 vol% SiC sample (a, b), (c) EDS point analysis of worn surface.
Figure 12. Wear track of (a) Al7075, (b) Al7075-5 vol% SiC, and (c) Al7075-10 vol% SiC samples.
Figure 13. (a–c) Morphology of worn debris for hot dynamically compacted samples: (a) Al7075, (b) Al7075-5 vol% SiC, (c) Al7075-10 vol% SiC.
Variation of friction coefficient (FC) vs. sliding distance is depicted in Figure 14. The results were obtained by wear test under 10 N normal load and 0.08 m/s sliding speed. As the figure shows, FC for Al7075 compacted sample has a relatively steady state between 0.6 and 0.8, whereas for Al7075-5 vol% SiC, it is initially higher for the sliding distance less than 100 m but decreases to about 0.5–0.65 for larger sliding distances. Lower average FC for Al7075-5 vol% SiC may be attributed to its higher hardness than Al7075 sample. Generally, as hardness increases, the actual contact area between the steel pin and the sample surface is reduced, and consequently, the value of FC diminishes.[17] Hosseini et al. [3] and Herbert et al. [2] also reported similar observation in their investigations. As Figure 14 shows, the FC curve for Al7075-10 vol% SiC reveals more fluctuations and higher FC values. For this sample, the FC varies between 0.9 and 1.1. The presence of such a dense and large fluctuations for Al7075-10 vol% is probably due to the high surface roughness and separation of hard SiC particles from Al sub-surface.[3]

Figure 14. Variation of friction coefficient for different nanocomposite samples.
4. Concluding remarks

The following conclusions may be derived for SiCnp reinforced Al7075:

1. The relative density reduces by about 2%, but the compressive strength increases by about 60%.
2. The specific strength (strength-to-density ratio) improves about 63%.
3. Microhardness increases about 20%.
4. Wear resistance of the dynamically compacted samples reduces significantly with respect to the monolithic material.
5. The SEM examination of the worn surfaces and debris reveals that delamination and abrasion are the dominating wear mechanisms.

Disclosure statement

No potential conflict of interest was reported by the authors.

References


