Wear and Frictional Characteristics of Carbon Fiber-(Al-Cu) Composites*

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The dry wear characteristics of chopped carbon fiber-(Al-Cu) composites containing 8.7 to 32 vol% CF produced by the powder metallurgical process were investigated by using a pin-rotating cylinder type wear test apparatus.

The wear volume of the composites was reduced to about 1/3 to 1/6 of that of sintered Al-Cu compact under loads, 0.98 N and 1.96 N, and to 2/3 to 1/3 under a higher load, 3.43 N. The reduction of the wear by introducing CF is considered to be smaller for higher contact pressures, and the wear-distance-ratio is larger for the initial stage of wear process, when the apparent contact pressure is high. These results may be due to lack of bond formation between CF and the metal matrix. The wear volume could be considered to be inversely proportional to the CF amounts, and decrease in the wear volume with increasing CF amount was much larger than the reduction of friction coefficient.

It may be presumed that the higher loading capacity of CF is rather responsible than its lower frictional characteristics for the good wear resistance of the CF-(Al-Cu) composites.

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I. Introduction

A great many techniques have been applied in an attempt to fabricate the carbon fiber reinforced composites with metal matrix⁽¹⁾⁻⁽¹²⁾. The powder metallurgical process is one of the suitable processes to produce composites with short carbon fiber chops⁽¹¹⁾⁽¹²⁾. In this technique, it is enough for sintering to heat the compact of carbon fiber and metal powder mixture up to only a fairly lower temperature compared to the melting point of metal, therefore, the degradation of the composites due to the carbide formation between CF and matrix metal can be controlled to be small.

Because of porous structure of the composites produced by this process, rather the wear resistant characteristics are much more expected⁽¹²⁾⁻⁽¹⁵⁾ than the mechanical strength, and their structure can be considered as a favorable

container for lubricants.

The present work was carried out to make it clear whether the excellent wear characteristics of CF-metal composites were due to the low frictional coefficient of CF or to their high load bearing capacity. For this purpose, the wear volume of composites and frictional force between composite and slider were measured for various loads by using a pin-rotating cylinder wear test apparatus designed for this experiment.

II. Experimental

1. Specimen preparation

In order to lower sintering temperatures and to break alumina film covering Al particles, which plays as a barrier against the formation of inter-particle bonding, Cu powder was added to Al powder to realize a liquid phase co-existing sintering condition by applying eutectic reaction of Al-Cu system. Carbon fiber (high modulus type fiber, chopped to about 30 μ m long) was added by 8.7, 12 and 32% in volume to Al-Cu powder mixture containing 10 mass%Cu. After having been stirred manually, these mixtures were pressed under a pressure of 590 MPa into a disk shape compact 25 mm in diameter and 4 mm thick and

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sintered in a vacuum.

The two-step sintering process was performed as follows; at first compacts were heated up to 673 K and were held there for 1.8 ks for degassing, and then at 733 K for 1.8 ks for the primary sintering. They were pressed again by the same amount of pressure as the first compression, and the secondary sintering was applied at 823 K for 3.6 ks. Wear test samples, a rectangular solid about $4 \times 4 \times 20$ mm³ in size, were cut from these compacts, and wear test was performed on the surface originally parallel to the disk surface. Before wear test, a test surface was polished by #2000 sandpaper.

2. Measurement of wear volume loss and frictional force

Schematic illustration of a wear test apparatus designed for the present work is shown in Fig. 1. A sample mounted on the sample

Fig. 1 Schematic illustration of wear test apparatus.

holder attached to the top of the arm was pressed to a cylindrical surface of a slider. Arbitrary pressure loads were available by changing weights. In the present work, 0.98, 1.96 and 3.43N (100, 200 and 350 gf) were employed.

The slider, a cylinder 25 mm in diameter and 200 mm long, of which the cylindrical surface was finished by grinding, was rotated by 10 revolutions per second which correspond to a sliding speed of 0.76 m/s. The wear volume loss was estimated from a length of the arc of a worn surface.

The frictional force measurement was carried out by mounting the sample on a test rig, as shown in Fig. 2. The spring constant and resonant frequency of the test rig were about 100 kN/m and 1 kHz, respectively.

III. Experimental Results and Discussion

1. Wear volume loss

Wear tracks of the sample are shown in Fig.

Fig. 2 Frictional force measuring rig.

Fig. 3 Sliding tracks on specimens, 0%(a) and 32 vol%CF(b). Wear debris is seen to be piled-up on both sides of the wear tracks and also packed in the pores on the composites (small dark patches in the sliding tracks).

3, where the sliding direction is left to right. In Fig. 3(a), a photograph of a sample containing no CF, wear debris like carbon black is seen to

be piled-up on both sides of the wear track, and the surface burn to form dark patches can be seen on the right half of the wear track. The

Fig. 4 Wear volume plotted against sliding distance for various loads, 0.98(a), 1.96(b) and 3.43 N(c). In (c), small triangles show the values obtained from the samples mounted on the frictional force measuring rig, as is shown in Fig. 2.

surface of the wear track is very rough, and hollows remaining after metal removal by being peeled off from the compact due to seizure are observed everywhere.

In Fig. 3, of the composite with 32 vol%CF, the sliding track shows a much finer and smoother structure than in (a). Small dark spots are wear debris packed in the pores of the composite. By an optical microscope, coarse pieces of debris which could be identified as a broken CF fallen off from the composite were hardly found in the piled-up debris.

The wear loss volume was obtained from the length of the wear tracks. In Fig. 4, the wear loss is shown as a function of sliding distance for three different amounts of loads, 0.98(a), 1.96(b) and 3.43N (c). In the figures, a linear relationship between the wear volume and sliding distance can be seen for the 0%CF sample for every load, i.e., this suggests that the wear loss does not depend upon an apparent contact area.

In contrast to this, the plots for samples containing CF can be considered to be of parabolic relationship. This means that the wear process changes due to the change in the contact condition as time passes. It is observed by an optical microscope that these composites contain a considerable amount of pores, estimated by weighing the sample, and the porosity was in the range from 10 to 15% for composites with 0 to 30 vol%CF. It may be reasonable to consider that these pores will be gradually filled up by debris during the early stage of the wear process. Through the wear debris as an agent, the slider may contact with three different parts of a sample, i.e., carbon fiber, patches of wear debris packed in the pores and metal matrix.

In the early stages, the slider may have a contact of greater part with CF, however, as the wear process proceeds, the contact area with the matrix metal will increase. After obtaining a uniform contact condition, the wear process will approach a steady one.

In Fig. 5, the wear-distance-ratio (WDR, the wear volume loss per unit sliding distance, i.e., slope of curves in Fig. 4) at a sliding distance of 5 km (in this stage, the wear rate can be considered to be constant) is plotted against loads.

Fig. 5 Wear-distance-ratio vs loads.

The figure shows that the variation of wear loss of composites with 8.7 and 32 vol%CF for loads is much smaller than that for CF amounts. In Fig. 6, WDR can be considered to be inversely proportional to CF amounts.

Here, it will be discussed whether the excellent wear resistant characteristics are due to the high load bearing capacity or to the low frictional coefficient of CF. From the appearance of wear tracks as seen in Fig. 1, and

Fig. 6 Wear-distance-ratio vs CF amounts.

considering that the reduction of wear loss does not simply correspond to the increase in CF amounts, it may be presumed that CF plays as a lubricant mostly in the form of fine wear debris mixed in the metal matrix.

If the wear resisting property is originated from the high load bearing capacity of CF, most part of the applied load will be supported by CF in the composite. Therefore, pressures acting on every CF will be proportional to the reciprocal of CF amounts. Provided that the wear loss is proportional to loads⁽¹⁶⁾, it may be concluded that Fig. 6 just demonstrates that a wear resisting property of these composites is due mainly to the high load bearing capacity of CF.

2. Frictional force

The variation of frictional coefficient μ of the composites during the sliding process is shown in Fig. 7. The coefficients increase rapidly from the value less than 1.0 to around 1.2 before sliding 0.5 km, and after that they remain constant. This may be due to an increase in contact area in such a way that the matrix metal initially contacted with the slider, flows to bury or cover the pores and exposed CF surface of the composites. It must be mentioned here that the frictional force was measured by a test rig with a relatively lower spring constant, about 100 kN/m, because the spring constant

of a testing apparatus is one of the most important factors controlling a frictional system⁽¹⁷⁾. The wear loss values measured by using this test rig are shown by small triangles in Fig. 4.

Results were obtained by two different systems for sample mounting, i.e., one is that in which the sample is mounted rigid on the sample holder, and the other is that in which it is mounted on a force measuring rig attached to the sample holder. In these two systems, the wear process of the composites seemed to proceed in almost the same condition, though wear loss is a little smaller in the case of testing by using the rig.

In Fig. 7, the sliding distance by which the frictional coefficient becomes constant is larger for the composites containing larger amounts of CF. Considering that the flow process of the matrix metal, as mentioned above, plays a main role in the early stage, it is possible to consider that a larger sliding distance is necessary to obtain a steady wear condition for the composites containing larger amounts of CF, because they are much porous. Because the CF can be also considered to have a higher wear resisting property than the matrix metal in the stage when the contact area between CF and slider is larger, the production rate of wear debris may be small.

For smaller sliding distances, the frictional coefficient of the composites is in the range from 0.5 to 1.0, i.e., much smaller than that of the steady wear process. This may be explained as follows; In this stage the slider mostly contacts with CF, probably because the amount of wear debris and metal flow are still small. On the other hand, the frictional coefficient of the sample containing no CF is high even at the beginning of sliding, and increases more slowly up to a relatively larger value than that of the composites. This suggests that the contact condition did not change so much through the whole wear process.

Optical micrographs of worn surface are shown in Fig. 8. In Fig. 8(a), lustrous patches and discolored patches produced by rubbing by the slider are seen. In contrast to this, (b) shows the smooth worn surface of CF, and also the lustrous area is larger as compared to

Fig. 7 Friction coefficient vs sliding distance.

Fig. 8 Optical micrographs of the worn surface of the specimens, 0%(a) and 32 vol%CF(b).

Fig. 9 Optical micrographs of the worn surface of the slider. Initial(a) and after wear test for 0 %CF(b) and 32 vol%CF(c).

(a). Presumably, the latter results from that the greater part of the load is supported by CF so that only a relatively smaller residual pressure will act on the matrix metal, and the debris of CF protects the metal surface from sticking by metal-metal contact between the matrix metal and slider. The worn surfaces of the slider are shown in Fig. 9. In Fig. 9(b), the matrix metal sticking to the slider surface can be seen as dark patches.

The fluctuation of frictional force is shown by curves inset in Fig. 10, and that of the composite with 8.7 vol%CF is much smaller compared to that of the compact containig no CF. By increasing CF amount, the width of this fluctuation was observed almost unchanged. This means that the wear debris of CF has lubricative and stick-protecting properties, however, the debris covering the sliding sur-

Fig. 10 Friction coefficient and wear volume as a function of CF content. The curves inset in the figure show the fluctuation of the frictional force for 0 and 8.7 vol%CF composites.

face may be presumed not to be effective to lower the friction, because the frictional force decreased by several ten percents while the sliding surface was being wiped by dry and clean paper. In order to consider the correlation between the frictional force and wear loss, they are plotted against CF amounts, as shown in Fig. 10. Both of them show downward curves nearly parallel to each other, however, the figure shows that the wear loss decreases more than frictional coefficient for an increase in CF amount. It may be concluded that even though the reduction of the frictional coefficient is small, introduction of CF is very effective to reduce wear loss of the CF-(Al-Cu) composites.

IV. Summary

Wear loss and frictional force were measured for CF-(Al-Cu) composites fabricated by the powder metallurgical process. Results obtained in this experiment are summarized as follows:

(1) The wear loss of the composites was reduced to about 1/3 to 1/6 of that of the compact containing no CF under loads, 0.98 and 1.96N, and to 2/3 to 1/3 under a higher loads, 3.43N. The reduction of wear caused by the existence of CF is larger for lower loads than that for higher loads, probably due to lack of bonding between matrix metal and CF.

(2) The wear-distance-ratio is more sensitive to CF amounts than to applied pressures.

(3) The amount of wear loss can be considered to be inversely proportional to CF amounts.

(4) The reduction of the frictional coefficient (from 1.8 to 1.3) is very smaller than that of the wear loss (from 3.0 to 0.2) caused by increasing CF amounts.

(5) It may be presumed that the higher loading capacity of CF is rather responsible than its lower frictional characteristics for the good wear resistance of CF-(Al-Cu) composites.

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REFERENCES

- (1) J. Morley: International Metal Reviews, Sept., (1976), 153.
- (2) K. Kobayashi and A. Kitamura: J. Japan Soc. Comp. Materials, **2** (1976), 60.
- (3) M. Morita: Kinzoku, **48** (1979), 2.
- (4) M. Shimura: Bull. Japan Inst. Metals, **18** (1979), 271 (in Japanese).
- (5) S. Ikegami and T. Ohsaki: J. Japan Soc. Comp. Materials, **6** (1980), 60.
- (6) Z. Hara: Kinzoku, **50** (1980), 12.
- (7) W. Kinner: Mat. Eng., **9** (1980), 64.
- (8) S. Tsai, D. Mahulikar, H. L. Marcus, I. C. Noyan and J. B. Cohen: Mat. Sci. Eng., **47** (1981), 145.
- (9) S. Umekawa: Kinzoku, **52** (1982), 8; A. Ohkura: *ibid*, **14**; E. Nakata: *ibid*, **18**.
- (10) Y. Murakami: Fukugozairyo no Genjo, Seminar Text of Japan Inst. Metals, (1983), 1; S. Umekawa: *ibid*, **9**; O. Watanabe: *ibid*, **17** (in Japanese).
- (11) A. Okada and H. Koguchi: Trans. Japan Inst. Metals, **24** (1983), 101.
- (12) J. P. Giltrow and J. K. Lancaster: Wear, **12** (1968), 91.
- (13) T. Masuyama: Kinzoku, **48** (1978), 10.
- (14) I. Shiota and O. Watanabe: *Composite Materials*, Proc. Japan U.S. Conference, Tokyo, (1981), p. 253.
- (15) A. Okada and H. Koguchi: J. Japan Inst. Metals, **46** (1982), 821 (in Japanese).
- (16) For example, H. Czichos: Tribology, Elsevier Sci. Pub. Co., London, (1978).
- (17) Y. Miyakawa, K. Seki and M. Nishimura: Junkatsu, **18** (1973), 323.