JTTEE5 8:553-558

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Characterization of the Wear Behavior of Thermal Sprayed Coatings

B. Wielage, S. Steinhäuser, T. Schnick, and D. Nickelmann

(Submitted 5 September 1997; in revised form 25 November 1998)

Friction and wear cause a reduction in quality and properties of materials, especially their surfaces. A wear test is a good method for estimating the wear of components and their durability. This article discusses some wear test methods and results of wear tests on thermal spray composite coatings (particle- and fiber-reinforced).

Keywords composite coatings, reinforcement, wear tests

1. Introduction

The surfaces of structural components are stressed by friction and wear during their use. Therefore, investigations on the tribological systems and the development of wear-resistant coatings and systems are desirable. Composite coatings, especially thermal spray composite coatings, are increasingly applied for protection against wear. These coatings offer the possibility of protecting the base material, especially against abrasive wear.

Composite coatings are applied on composite materials and consist of at least two phases: the matrix (metal, ceramic, and polymers) and one or more incorporated phases (particles or short or long fibers). The unique properties of the composite material results from the combination of the properties of individual materials. Coupled with this is the advantage of composite coatings with properties that can be adjusted to a large extent.

The examination and investigation of thermal sprayed composite coating forms is difficult due to the heterogeneous character. Therefore, the selection of the appropriate testing method is of great importance. It must also be discussed how the test results are evaluated in consideration of the inevitable wide distribution in results. Moreover, it is indispensable to use several testing methods simultaneously to achieve an objective appraisal. This article indicates possible investigation methods and discusses the testing and evaluation problems experienced for thermal spray coatings.

2. Experiments

2.1 Overview of Wear Tests for Thermal Sprayed Coatings

Wear tests enable information about properties of composite coatings under load. For the characterization of the wear behavior of the thermal sprayed and other coatings there are methods for simulation of basic wear mechanisms, investigations on tribological relevant materials properties, integral wear test methods, and tests, which are used in practice (Fig. 1).

The wear of a material influences the tribological system, which encloses the friction bodies, the stress conditions (e.g., surface pressure and friction velocity), and the surrounding medium. The wear resistance of a material is not a simple material property but a system attribute, which has to be taken into account with respect to wear tests. It is required to carry out a complex wear test (tribological testing cycle), represented in Fig. 1.

The wear damage of materials (components, machines, and installations) expresses itself in the wear rate (e.g., the loss of material volume), the wear appearance (e.g., damage morphology and nature of wear particles), and, possibly, cracking from the material surface into the material interior and deterioration of the materials properties, such as fatigue strength). Tribological stress, contact conditions, and the friction-element composition lead to recognizable wear. This can be traced back to individual or superimposed effects of basic wear mechanisms such as abrasion, adhesion, and fatigue processes. These can be aggravated by corrosion processes, termed as tribocorrosion.

An initial first was to simulate these mechanisms in a wear test (Fig. 1). A scientific perception can thereby be gained, and prediction on the suitability and material selection in order of coating priority can be made. In the next step of the tribological test cycle, that is, test by integral wear test methods (Fig. 1), the correlation of the product properties becomes more clear. However, the costs for these tests is higher, and they are more demanding. During examination of original systems (Fig. 1), the test is only slightly simplified to enable a better correlation to the product. This in particular applies to field trials (Fig. 1). The relevant materials characteristics must always be examined concurrently (Fig. 1). Results of such investigations and interactions with the tribological factors are influenced by the morphology of coatings and wear appearance, materials properties, and debris generation.

2.2 Examples for Wear Test Methods

Testing Methods for Simulation of Basic Wear Mechanisms. In the abrasive wear test, the test device (Fig. 2), a diamond indenter of well defined geometry such as Vickers indenter, was used. This indenter enters the surface as a consequence of normal load (F_N = 20, 50, 100, 150, or 200 N) and

B. Wielage, S. Steinhäuser, T. Schnick, and **D. Nickelmann,** Institute for Composite Materials, Technical University of Chemnitz, Germany. Contact e-mail: bernhard.wielage@wsk.tu.chem.

scratches the surface layer as a result of a tangential force. During the experiment, the area of the scratch, A_R, (scratch width, b_r; scratch length, L_R) and the tangential force, F_T, were determined, and the scratch energy density, w_R, was calculated. A high scratch energy density corresponds to a high resistance against abrasive wear.

For the adhesive wear test, in the test facility, a flangelike counter body was attached to a torque rod by which a torsional moment, M_t, was generated via a set of weights (Fig. 3). The sample was secured against distortion and pressed by a normal force, F_N, against the counter body. As the normal force was applied, the weights were removed, and the torque, M_t, was main-

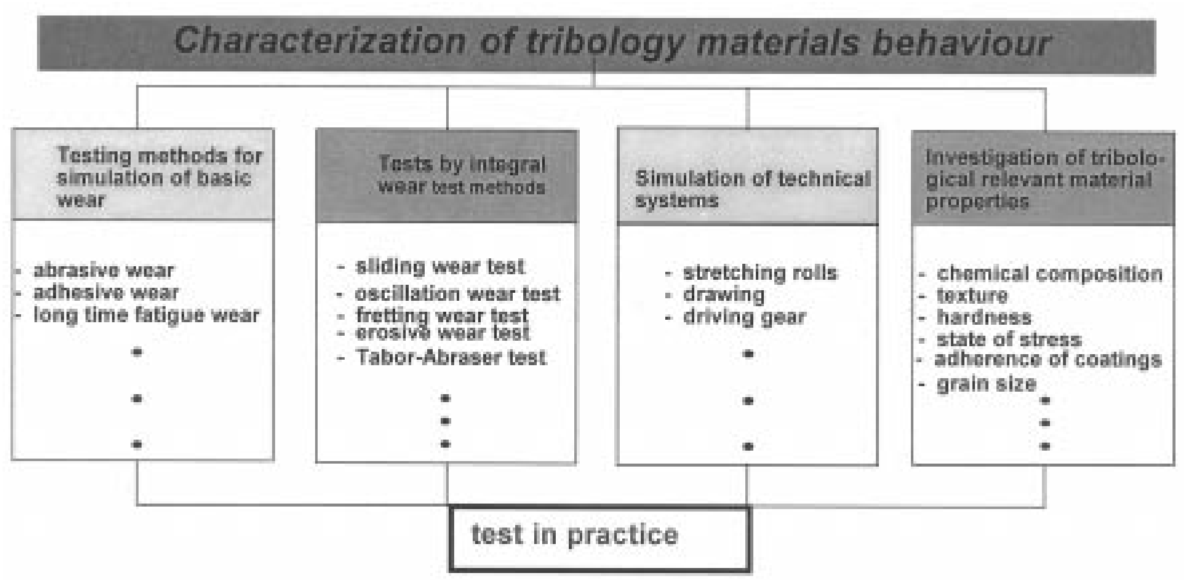

Fig. 1 Overview of wear test methods (tribological testing cycle)

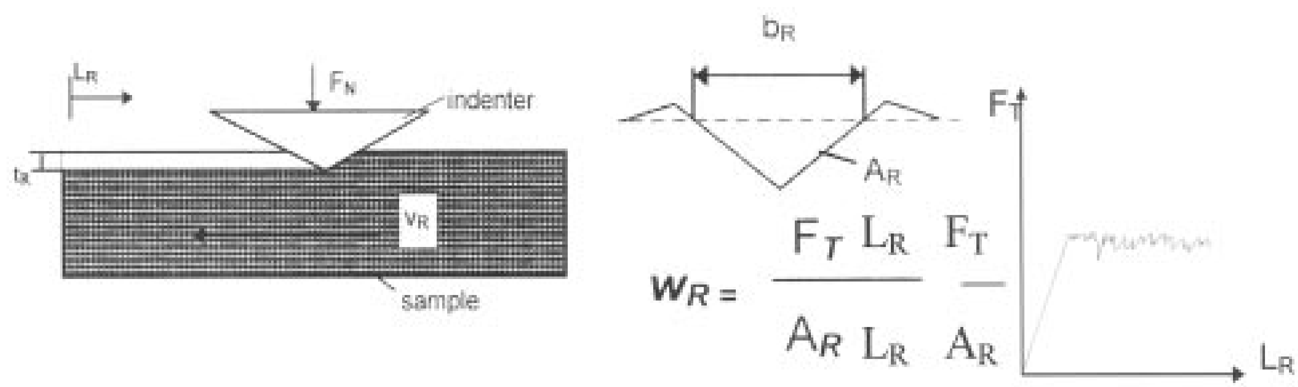

Fig. 2 Pattern of the abrasive wear test

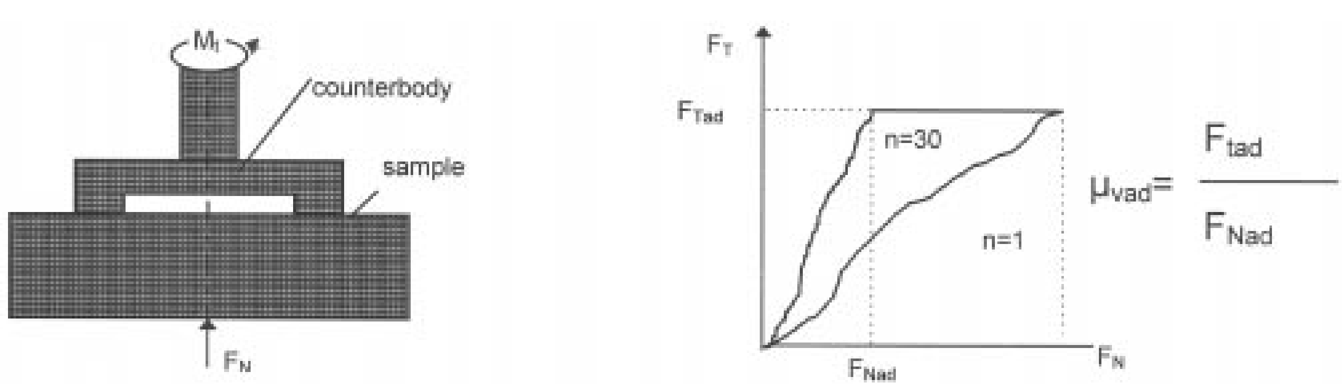

Fig. 3 Pattern of the adhesive wear test (n, number of test cycles)

tained only by adhesion forces. On relieving the normal force the counter body begins to move back to the starting position. The adhesion number, μ_{vad}, was a function of the tangential force for the adherence touch, F_{Tad}, and the normal force, F_{Nad} (force normal to the adhesion).

For the oscillation wear test, the test under oscillation load (Fig. 4) created a wear trace, a calotte, in the specimen. The specimen oscillates (amplitude 0.5 mm) under the counter body. Parameters of the test are the load, F_N, ranging from 0.5 to 20 N; the frequency, f, 20 Hz; and the testing time, in this case 30 min. The counter body is a steel ball (100 Cr6 hardened or a ceramic) of 4 mm diameter. For the characterization of the wear behavior of the coatings the linear wear, w_L, is determined. This linear wear is obtained from the data of the calotte width, d_s, and the counterbody radius, R.

Test by Integral Wear Test Methods. The sliding wear test can simulate adhesive and abrasive wear (Fig. 5). The counter body (a hollow cylinder, outside diameter, 7 mm; inside diameter, 5 mm; C100 W1 hardened) rotated by a torque is pressed against a specimen. The intensity of wear, I_h, is the characterization parameter for the wear behavior and is calculated by the wear mark depth Δh and the wear distance, s. The other testing parameters are the testing velocity, v; 0.47 m/s; and the load, p, 1.06 to 3.6 MPa.

The wear of the specimen also can be characterized by an abrasive-rolling wear in the Taber abraser test. Two grinding rolls press the specimen disk (diameter 100 mm, Fig. 6). The disk revolves, and the grinding rolls receive a relative movement associated with slip. A linear contact zone exists between the grinding rolls and the disk. The testing parameters are the load, F_N (2.5 to 10 N); the velocity, v, 260 mm/s; and the wear distance. The amount of wear is a measure of the loss of the specimen disk per, for example, 1000 wear turns.

Investigations of Tribological Relevant Material Properties. The characterization of the structure of a thermal sprayed coating was an example. The composition of the materials, the structure, and the surface of thermal spray coatings are the properties that influence their behavior under wear. Thermal spray coatings have a heterogeneous structure. Figure 7 shows this as an extreme case, while more homogeneous coatings are quite attainable.

This complex structure makes it difficult to measure to the material properties. The cross section of the sample reveals information about the porosity (content, size, and distribution of pores), the content of reinforcement particles, their distribution and incorporation into the matrix, as well as damage of the particles or fibers during the spray process.

3. Examples and Results

Figure 8 shows the investigations of thermal spray particle-reinforced aluminum and aluminum-silicon alloy onto the basic material AlZnMgCu1.5 at the East-West Institute Surfacing Cooperation (EWISCO) program. The EWISCO group was founded in 1991 and consists of the Paton Welding Institute, Kiev, Ukraine; the Powder Metallurgy Association Minsk, Belorussia; the Institute for Composite Materials of the Technical University Chemnitz, Germany; and the Materials Science Institute of the Technical University Aachen, Germany, as the coordinator.

All the thermal spray composite coatings increased the wear resistance of the basic material. But the thermal spray composite coatings exhibited a different wear resistance in the scratch energy density test, in the sliding wear test, and the oscillation wear test. This indicates that the spread in the scratching energy density, w_R, was the largest. This is due to the fact that the small indenter, compared to the coating components, was influenced by inclusions, particles, and pores. It is better to examine homogenous materials with this procedure. The variation values of coating variation, B, show only a small scatter, while the alloy of

Fig. 4 Pattern of the oscillation wear test (Ref 1)

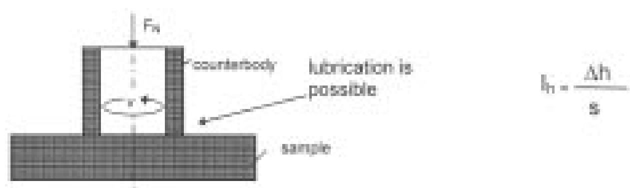

Fig. 5 Pattern of the sliding wear test

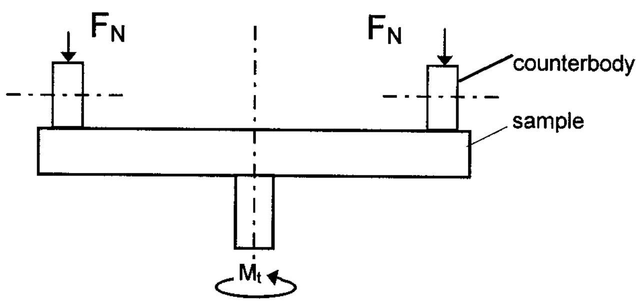

Fig. 6 Pattern of the Taber-abraser test

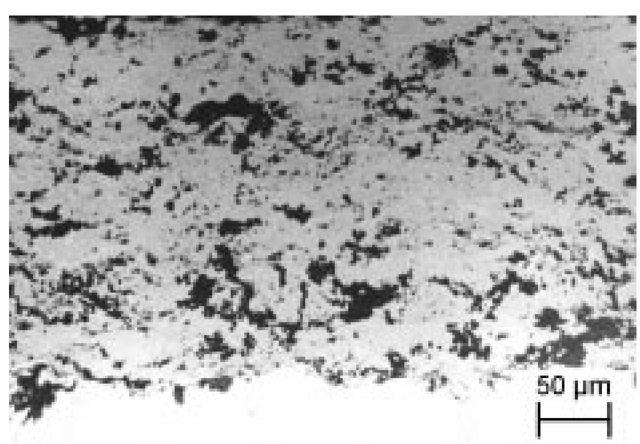

Fig. 7 Fe-TiC thermal spray coating with heterogeneous structure (Ref 2)

variation, D, shows much larger scatter. The same comparative trend is exhibited for C and E. Particle types and contents have a further influence, as could be seen for the coatings B and C. Figure 9 shows the layer, A, of the aluminum coating reinforced with aluminum oxide. Similar cross sections were obtained with the inclusion of SiC into the coating matrices.

The SiC and Al_2O_3 particle-reinforced aluminum coatings (Ref 3) demonstrate similar results to the other coatings. The embedded particles improve the wear resistance of the aluminum coating.

The scatter became far smaller when using test methods that are not as sensitive to microstructural homogeneities. However, the differentiation of the individual coatings and their components decreased. Therefore, the test result is more similar to practical circumstances where superposition of several tribological stress occurred and the effect was complex.

The addition of 50 wt% SiC to the aluminum powder resulted in aluminum-silicon carbide coatings with a particle content of 23% (Fig. 10). An improvement in the wear resistance compared to pure aluminum coatings could be determined in the Taber abraser test (Fig. 11).

Compared to the silicon carbide particles, raising the content of aluminum oxide particles in the aluminum layers could be achieved. Wear tests on aluminum-aluminum oxide coatings in the aluminum layers show that the inclusion of the particles causes an improvement in the wear resistance in the Taber abraser test (Fig. 12). An 18 wt% content of the aluminum oxide in the coating (25% powder content) reduces the mass loss by half. The increase in aluminum particles, up to 50 and 75%, produces coatings with particle contents of between 32 and 38%, which exhibited improved wear resistance.

In spite of a higher particle content in the aluminum-aluminum oxide compared to the aluminum-silicon carbide coatings, no significant differences in the wear resistance could be determined in the Taber abraser test.

The performance of these coatings is different during the sliding test. The intensity of the sliding wear in the silicon carbide reinforced layer is considerably lower compared with the aluminum oxide reinforced layers.

The possibility of increasing the content of aluminum oxide particles in the sprayed coatings does not cause a reduction of the sliding wear. In spite of the higher particle content of the aluminum oxide reinforced coatings, the sliding wear results were three times higher compared to the silicon carbide reinforcement (Fig. 13, Ref 4). The abrasive wear resistance (Taber abraser test) increased with the growing particles content.

It has been demonstrated (Ref 5) that it is possible to produce short fiber reinforced thermal sprayed coatings. Figure 14 shows a cross section of a carbon short-fiber reinforced aluminum coating without any post treatment. The post treatment to

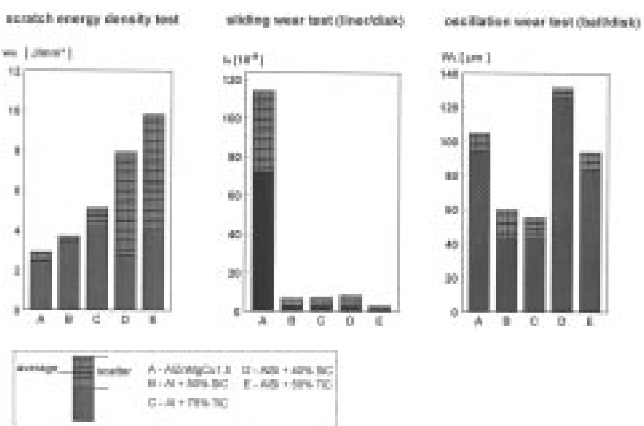

Fig. 8 Particle-reinforced aluminum and aluminum-silicon alloy (Ref 3)

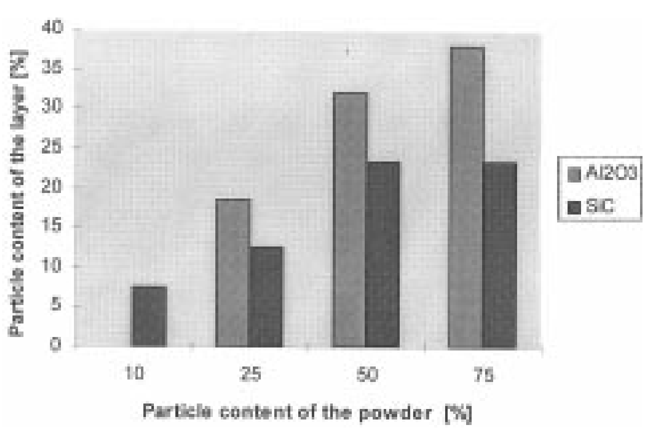

Fig. 10 Content of reinforced components (Ref 4)

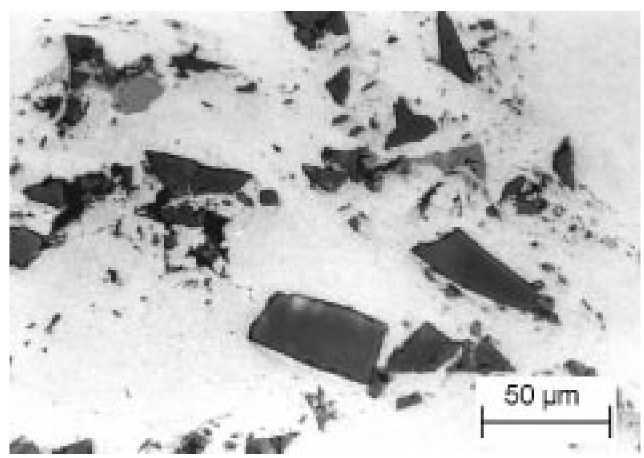

Fig. 9 Al_2O_3 reinforced aluminum coating

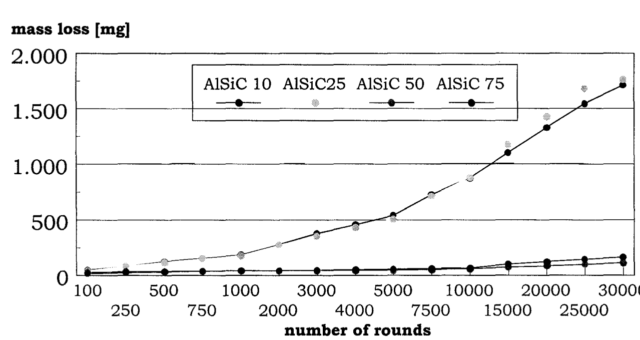

Fig. 11 Taber-abraser test on SiC particle-reinforced aluminum coatings (Ref 4). The upper curve represents the 10 wt% SiC coating, while the lowest curve represents the 75 wt% SiC coating.

reduce the porosity and to improve the fiber embedding consists in pressing (Fig. 15). The metallographic investigations on the thermal sprayed carbon short-fiber reinforced aluminum coating (fabricated by vacuum plasma spraying) show that the fiber distribution (content 8 vol%) and the porosity (content 5 vol%) are connected. The microstructural feature served as a barrier and hindered the continuous flow of the molten aluminum.

Figure 16 shows the results of the Taber abraser test and the oscillation wear test. Clearly, the mass loss of the unreinforced coating is much higher than the mass loss of a carbon fiber-reinforced aluminum coating. The oscillation wear was determined in correlation with the fiber content. An improvement of the wear resistance with increased fiber content was also observed.

4. Conclusions

Wear test methods and investigations on the thermal sprayed composite coatings were presented in this article. The wear tests

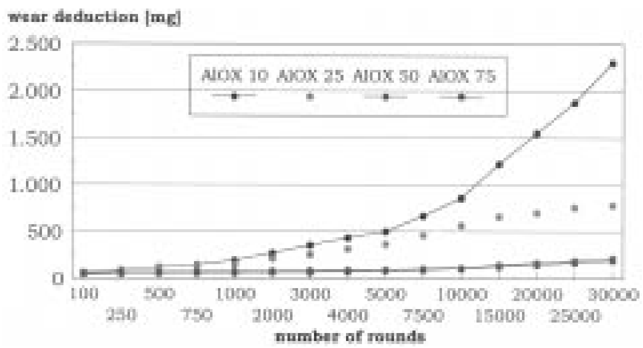

Fig. 12 Taber-abraser test on Al_2O_3 particle-reinforced aluminum coatings (Ref 4)

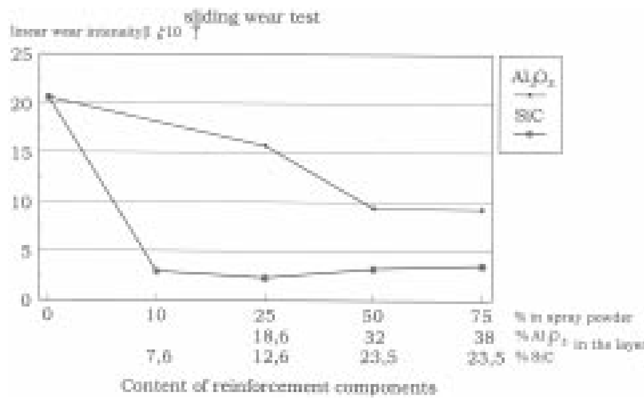

Fig. 13 Sliding wear test on particle-reinforced aluminum coating (Ref 4)

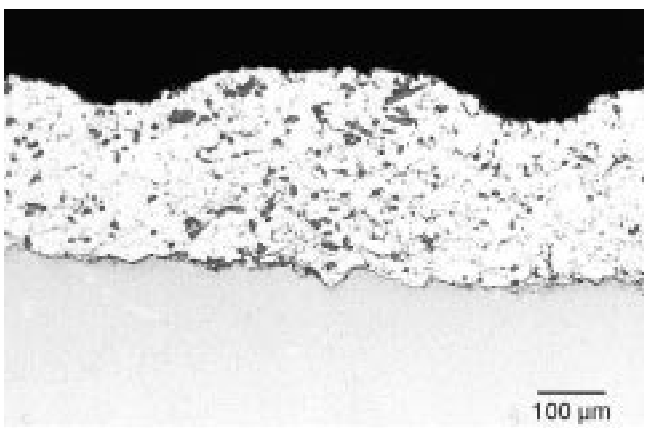

Fig. 14 Carbon short-fiber reinforced aluminum coating (Ref 2)

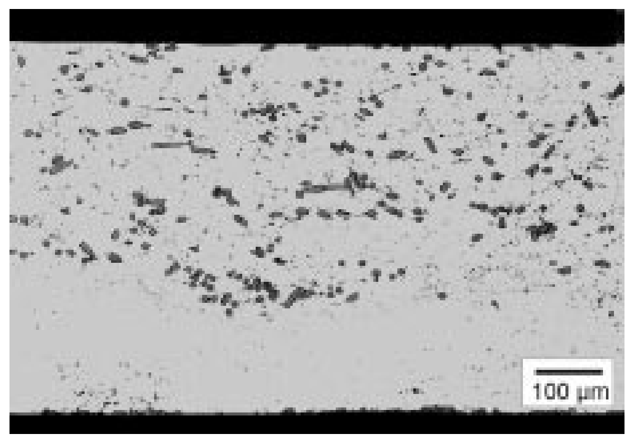

Fig. 15 Carbon short-fiber reinforced aluminum coating after post treatment (Ref 2)

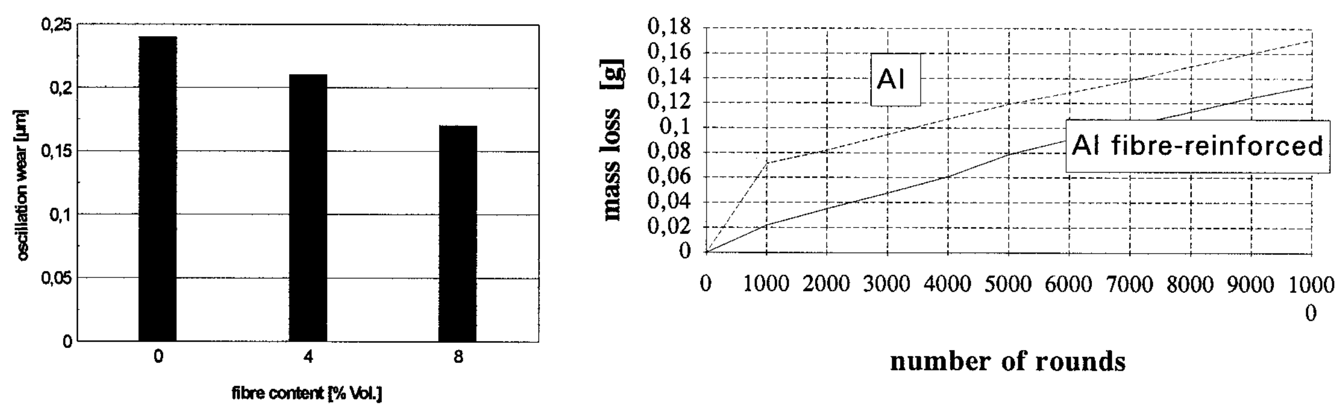

Fig. 16 Aluminum coatings and aluminum-carbon fiber reinforced coatings. (a) Oscillation wear test. (b) Taber-abraser test (Ref 2)

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established the response of the composite coatings toward abrasion and adhesion in comparison with pure materials. These coatings can inhibit detrimental changes from friction and wear. The material behavior was investigated under well defined tribological conditions and characterized by data relevant to wear. Some general summary comments are pertinent to these measurements:

- Wear investigations are important and very informative; however, they are very complicated.
- Wear behavior as a system attribute must be reflected in the testing methods.
- Attention should be paid to the tribological test cycle.
- Special problems appear in the case of heterogeneous materials (e.g., thermal sprayed composite coatings).
- Methods and results must be discussed and evaluated critically.

Acknowledgments

The authors would like to acknowledge the employees of the Institute of Composite Materials, the scientists, laboratory technicians, and students, who cooperated in this study.

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