Low Cycle Fatigue Behavior of Aluminum/Stainless Steel Composites

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Stainless steel wire-reinforced aluminum matrix composites having a wide range of fiber volume fraction (5-56%) were fabricated under optimum conditions of temperature, time, and pressure of hot pressing. These composites were tested in plane bending to complete fracture under cyclic loading at a suitable strain level. The test results were analyzed by computer to obtain a statistically valid mathematical relationship between low cycle fatigue life and fiber volume fraction (V_f) of the composites. This relationship is expressed as: $\ell nN = 7.57 - 4.25V_f + 66.47V_f^2 - 85.12V_f^3$ where N is the number of cycles to fracture of the composites. Fatigue life reaches a peak value for the composites having a fiber volume fraction of about 50% and is about 50 times higher than that of the matrix at a strain level of 0.65%. Scanning electron microscopy studies on the fractured surface of the composites revealed many characteristic features of fatigue damage in the composites. Suitable fatigue damage micromechanisms are proposed and discussed.

Introduction

METAL matrix composites are very promising materials for aerospace and defense applications because of their improved performance and cost competitiveness.[1] Aluminum/boron, titanium/boron, and titanium/silicon carbide fiber composites are used in lightweight airframes and gas turbine engine components. Tungsten wire-reinforced superalloy composites are potential high-temperature materials and find their applications in turbine blades with a use-temperature *increase* of up to 150 K above that of commercial superalloys.[2] Metal matrix composites offer a good flexibility of introducing the principle of reinforcement in metals in the preliminary design stage.[3] This design flexibility leads to a low life-cycle cost. This is evidenced in Fig. 1, which shows a substantial reduction in specific fuel consumption in advanced aerodynamics and structures.[4] The increasing interest in metal matrix composites as future structural materials[5] is apparent in Fig. 2. Some of the main reasons behind such widespread attention to these composites are 1) a specific modulus about an order of magnitude greater than that of fiber-reinforced resin matrix composites; 2) a nearly isotropic elastic modulus; 3) better off-axis strength; 4) high ductility and toughness[3,6]; 5) desirable high temperature properties and stability; 6) design flexibility; and 7) lower life-cycle cost. However, there remains much to do in order to understand the fundamentals behind the mechanical behavior of these composites. One of the important areas is their fatigue behavior, for which only limited work has been reported in the literature.[7-11]

Fatigue results for potential metal matrix composites for structural applications are presented in Tables 1-3. Some of the numerical values have been obtained from fatigue curves, and all of the results have been arranged so that certain broad conclusions can be drawn. It is apparent that, in general, the fatigue limits of the composites are higher than those of the matrix materials; fatigue limit for a particular composite increases with increasing fiber volume fraction, and the fatigue ratios [fatigue limit/ultimate tensile strength (UTS)] of the composites are generally lower than or only comparable to those of the matrix (Tables 1 and 2).

The above conclusions are also valid for the elevated temperature fatigue results (Table 3) available for superalloy/tungsten, titanium/silicon carbide, and aluminum/beryllium composites. In addition, it should be noted that as the test temperature increases within the range investigated, the fatigue ratio is only slightly reduced. Thus, these composites offer excellent fatigue resistance at elevated temperatures.

The purpose of the present investigation was to understand the fracture mechanisms of composites under cyclic loading and to propose a suitable means of improving the fatigue ratio without compromising their tensile strength. The possible fracture mechanisms involve a number of discrete processes. For example, a crack may initiate at a stress raiser on the outer surface of the specimen, at the broken fibers, and/or at the brittle interface inside the specimen. Also, the crack growth may be impeded because of crack branching in the matrix, delamination at the interface, crack blunting by the matrix, shielding of crack tips by fibers, or a combination of some or all of these damage processes.

Gouda et al.[24] observed early surface crack development at cycles lower than 10% of the total number of cycles to complete fracture of aluminum/boron composites. This shows that there is not much to greatly delay the crack initiation in composites, and this will depend primarily on the notch sensitivity of the matrix.[10,23] Thus the answer to improved fatigue resistance apparently lies in preventing crack propagation for the most part of the cyclic life of composites. One hopes that this can be achieved by increased fiber content, with an assumption that the composites eventually will fail because of the link-up of a large number of microcracks[11,16,24] rather than a rapid propagation of a dominant transverse crack.

Hancock and Shaw[25] reported about a 20% increase in fatigue life of aluminum/boron composites at a fiber volume fraction of 25%. However, this favorable effect of the so-called weak interface can be made convincing only by demonstrating an improved fatigue ratio over a wide range of fiber volume fraction. This will certainly require more experimental results than are currently available. However, a weak interfacial bonding is not a practical means of achieving a desirable level of fatigue resistance in composites because the interfacial bond strength should probably exceed the strength

Presented as Paper 83-0806 at the AIAA/ASME/ASCE/AHS 24th Structures, Structural Dynamics and Materials Conference, Lake Tahoe, Nev., May 2-4, 1983; received May 1983; revision submitted April 3, 1984. Copyright © American Institute of Aeronautics and Astronautics, Inc., 1984. All rights reserved.

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of the matrix in most applications to maintain sufficient transverse properties. It is in this context that this paper addresses the fatigue behavior of composites having an interface relatively stronger than the matrix. Such an interface is likely to enhance branching of cracks by tensile failure in the matrix.[24,26] In addition, composites may exhibit matrix delamination adjacent to the interface at high fiber volume fractions because of the reduced interfiber distance.[27,28] The following section deals with the fabrication of composites having a wide range of fiber volume fraction.

Fabrication Method

The powder metallurgy method is very important for the fabrication of composite materials.[29] This method can use powder matrix of low melting to very high melting metals and alloys over a wide range of compositions; reinforced with either continuous or discontinuous fibers to provide net or near-net shape of even complicated finished products. The powder metallurgy technique further provides excellent control over fabrication conditions such as temperature, time, and pressure involved in hot die pressing or hot isostatic pressing (HIP).

In the present work, 304 stainless steel wire (0.3 mm diam) reinforced aluminum matrix composites were fabricated by hot die pressing under various temperatures, times, and pressures. The properties of aluminum powder and stainless steel wire are presented in Table 4. The hot pressing parameters were optimized to control diffusion bonding be-

Table 1 Conventional high cycle fatigue results for aluminum/boron composites

Material	V_f	Fatigue limit (for 10^7 cycles), MNm^{-2}	UTS, MNm^{-2}	Fatigue ratio	Stress ratio	Source Ref.
6061 Al	0.0	111	152	0.73	0.2	7
6061 Al/B	0.22	324	579	0.56	0.2	12
6061 Al/B	0.25	456	724	0.63	0.2	7
Al/B	–	–	–	0.57	–	13
6061 Al/B	–	–	–	0.60	–	14
6061 Al/B	0.30	483	–	–	0.2	9
6061 Al/B	0.40	617	1186	0.52	0.2	9
6061 Al/B	0.50	772	–	–	0.2	9
6061 Al/B	0.40	569	1138	0.50	0.1	12
6061 Al/B	0.40	936	1248	0.75	0.4	15
6061 Al/B	0.60	1385	1951	0.71	0.4	15
2024 Al/B	0.20	–	–	0.42	0.2	7
1100 Al/B	0.25	–	–	0.76	0.2	7
Al/Borsic	–	174	300	0.58	0.1	16
6061 Al/Borsic	0.40	578	1014	0.57	0.2	9

Table 2 Conventional high cycle fatigue results for aluminum/graphite, aluminum/stainless steel, and aluminum/beryllium composites

Material	V_f	Fatigue limit (for 10^7 cycles), MNm^{-2}	UTS, MNm^{-2}	Fatigue ratio	Stress ratio	Source Ref.
201 Al	0.0	55	183	0.30	0.1	10
201 Al/graphite	0.31	254	552	0.46	0.1	10
6061 Al/graphite	0.31	303	605	0.50	0.1	10
Al/graphite	–	–	–	0.32	–	17
2024 Al	0.0	126	500	0.25	−1.0	18
2024 Al/stainless steel	0.25	177	1196	0.16	−1.0	18
7002 Al	0.0	165	372	0.44	0.1	19
7002 Al/Be	0.33	253	517	0.49	0.1	19

Table 3 Elevated temperature, low cycle fatigue results for metal matrix composites

Material	V_f	Test temperature, K	Fatigue limit,[a] MNm^{-2}	UTS, MNm^{-2}	Fatigue ratio	Stress ratio	Source Ref.
	0.20	1030	276	322	0.86		
$FeCrAlY/W\text{-}1\%ThO_2$	0.35	1030	427	563	0.76	0.1	20,21
	0.20	1250	167	236	0.71	(approx.)	
	0.35	1250	316	425	0.74		
Ni/W	–	300	–	–	0.80	–	20,22
Ti	0.0	920	138	230	0.60	0.0[b]	
Ti(6Al-4V)/SiC	0.25	920	313	580	0.54	0.0[b]	23
7002 Al	0.0	530	90	148	0.61	0.1	
7002 Al/Be	0.33	530	207	260	0.80	0.1	19[c]
7002 Al/Be	0.33	300	255	538	0.47	0.1	

[a]Fatigue limit values given here correspond to different number of cycles between 10^3 and 10^6 cycles. [b]Strain ratios. [c]High cycle results.

Table 4 Properties of aluminum power and stainless steel wire

Material	Properties	Results
Aluminum powder Grade D (INDAL)	Apparent density	0.982 g/cm^3
	Tap density	1.218 g/cm^3
	Flow rate	91.25 s (50 g)
	Sieve analysis:	
	−80 +150	78.5%
	−150 +200	19.0%
	−200	2.5%
Hot-pressed aluminum matrix (800 K, 1 min, 140 MNm^{-2})	Tensile strength	90 MNm^{-2}
Stainless steel wire (304 grade, 0.3 mm diam)	Tensile strength	770 MNm^{-2}

Table 5 Tensile strength and fatigue life data of aluminum/stainless steel composites

V_f	UTS, MNm^{-2}	Fatigue life cycles	Fatigue life / UTS, (MNm^{-2})$^{-1}$	Region (see Fig. 4)
0.1	81	1939	23.8	
0.05	118	1832	15.6	I
0.10	152	2263	14.9	
0.20	215	5590	27.8	
0.30	271	21570	79.5	
0.40	320	63419	198.2	II
0.45	341	85915	251.6	
0.50	361	91354	252.9	
0.55	379	71527	188.6	
0.60	395	38687	97.9	III

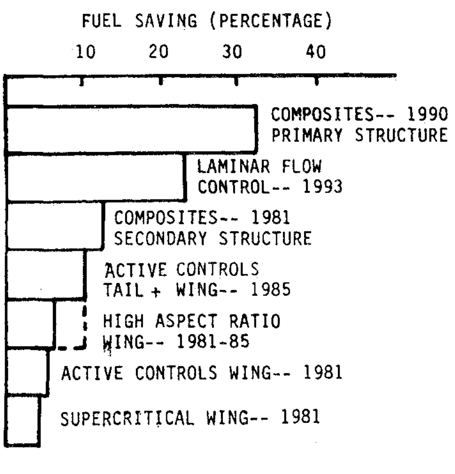

Fig. 1 Predicted fuel savings in aerodynamics and structures.[4]

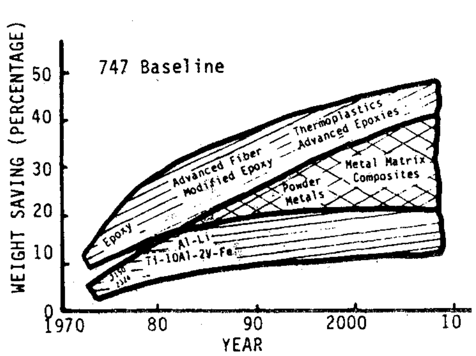

Fig. 2 Trend in potential structural weight savings.[5]

tween matrix and fiber in order to obtain composites having maximum tensile strength at any fiber volume fraction. The optimum hot pressing temperature, time, and pressure thus established are 800 K, 1 min, and 140 MNm^{-2}, respectively. The nature of the interface was characterized by optical scanning electron microscopy and microprobe analysis. These details and the experimental setup and procedure to establish optimum fabrication conditions, including the tensile test results, are presented in Refs. 27 and 28. The composite specimens for fatigue test were fabricated under the optimum conditions of hot pressing over a wide range of fiber volume fraction. These specimens had an interface somewhat stronger than the matrix. The next section deals with testing of composites.

Fatigue Test

The proper choice of a suitable test method is necessary to obtain reliable and useful fatigue results acceptable in advanced design concepts. Fatigue data presented in Tables 1 and 2 were obtained by conventional high cycle axial fatigue tests; those in Table 3 refer to low cycle fatigue tests. Recently, Bucci[30] demonstrated that strain-based low cycle fatigue data are more reliable than the conventional stress-based high cycle fatigue data in metals and alloys. His observations are of particular importance in composite materials that are likely to experience high stress and strain cycling in many advanced applications.[2] In such applications a low cycle fatigue test involving high stress and constant plastic strain is very desirable because it simulates the actual service conditions to a great extent. Low cycle fatigue data, however, can be obtained from either axial or flexural cyclic loading of the specimens. The choice of bend testing lies in its simplicity, specimen stability at high strain levels, and minimal equipment costs. A disadvantage is that the stress and strain are not uniform throughout the cross section and therefore not amenable to rigorous analysis. However, information applicable to materials evaluation and structural design can be developed confidently, as evidenced by the fact that data obtained by flexural fatigue tests[31] and axial fatigue tests[32] for 70-30 cupro-nickel were identical for all practical purposes. It is not known whether this observation will hold true in composites; the choice in the present investigation was solely dependent on the availability of a low cycle plane bending machine. Composite specimens (75 mm long, 12 mm wide, and 3 mm thick) were tested in plane bending at 55 cycles/min. Further details of the equipment and the testing procedures are described in Ref. 27.

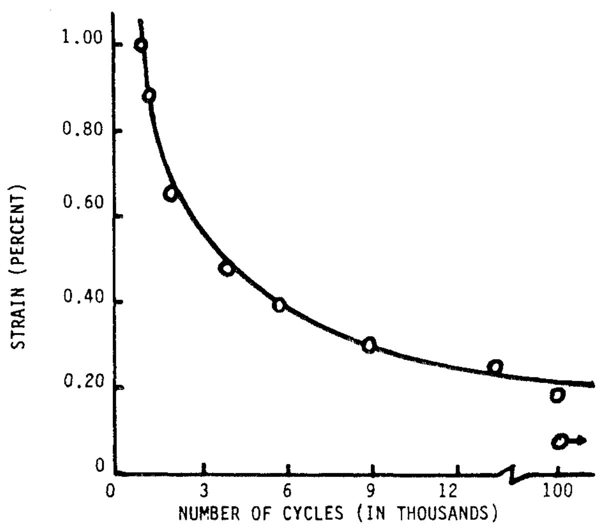

Fig. 3 Strain-controlled plane bending low cycle fatigue for hot-pressed aluminum matrix. (Arrow indicates termination of test at 10^5 cycles.)

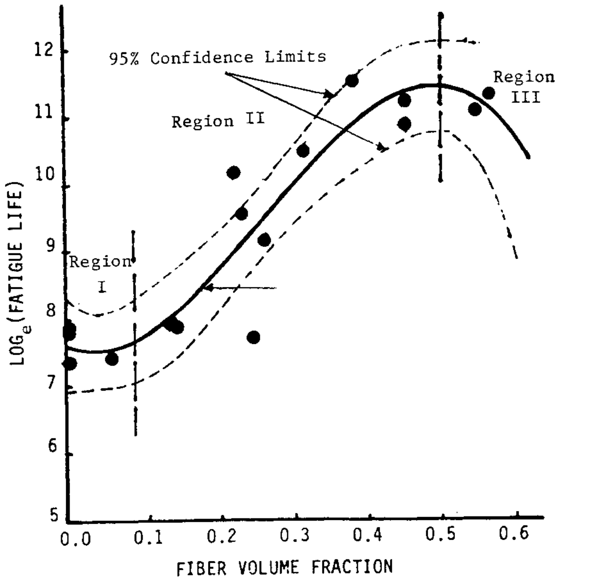

Fig. 4 Dependence of low cycle fatigue life of hot-pressed aluminum/stainless steel composites on fiber volume fractions at a strain of 0.65%.

Fig. 5 Primary and secondary cracks in a fiber cross section, and matrix striations at the interface.

Results and Analysis

Strain-controlled low cycle fatigue life of composites has been presented in terms of the number of cycles at complete fracture of the specimens. Composite specimens having a wide range of fiber volume fraction were all tested at a single high strain level of 0.65%. A judicious choice of this strain level was obtained by testing aluminum matrix specimens fabricated under conditions identical to those of the composites and plotting a curve for their fatigue lives against strains ranging from 0.03 to 1% (see Fig. 3). It was expected that at the high strain of 0.65%, all the composite specimens will most probably fail under a low cycle range limit of about 10^5 cycles.

The fatigue results of the composites are presented in Fig. 4. These results were analyzed by computer to assess their statistical validity and to find their best mathematical representation. Linear, quadratic, and cubic regression analysis were attempted with fiber volume fraction (V_f) as an independent variable and fatigue life (N) as a dependent variable. Mathematical relationships between N and V_f, as well as computer plots for best-fit curves, revealed that none of these represented the experimental data well. Next, attempts were made to obtain logarithmic relationships between fiber volume fraction and fatigue life. The mathematical relationships thus obtained were found to be acceptable.

Linear regression

$$\ln N = 7.42 + 7.67 V_f \tag{1}$$

Quadratic regression

$$\ln N = 7.36 + 8.61 V_f - 1.80 V_f^2 \tag{2}$$

Cubic regression

$$\ln N = 7.57 - 4.25 V_f + 66.47 V_f^2 - 85.12 V_f^3 \tag{3}$$

Computer plots of curves represented by Eqs. (1-3), in general, were found to represent the experimental data well. However, the best representative curve was given by Eq. (3) and is shown in Fig. 4 as a continuous curve. Figure 4 also includes two broken curves which are the 95% confidence limits for the best-fit curve. The 95% confidence limits[33,34] represent a band having a 95% probability of including the true fatigue curve that will be determined from an infinitely large number of fatigue life data over a wide range of fiber volume fraction.

It is apparent from Fig. 4 that the fatigue fracture behavior of fiber reinforced composites is different in different regions of fiber volume fraction. This necessitated scanning electron microscopy (SEM) studies on fractured surfaces of the composites in order to understand the possible different micromechanisms operative under cyclic loading. The details of the fractographic studies and the proposed fatigue damage micromechanisms are discussed in the next section.

Discussion

It is apparent from Fig. 4 that the fatigue curve has three distinct parts. These parts correspond to specific ranges of fiber volume fraction. However, the specificity of any fiber volume fraction ranges may not hold true for other fatigue curves drawn at different strain levels, despite a great likelihood of those curves having a similar shape. Thus, it is deemed proper to designate the different parts of the curve in Fig. 4 as regions I, II, and III, corresponding to low, medium, and high ranges of fiber volume fraction without assigning any numerical value. In the first region, the fatigue lives of the composites and the matrix are almost the same; the fatigue life of composites rapidly increases in region II, and finally shows a downward trend (region III) after it attains a peak value at the end of region II. The possible damage micromechanisms operative in these regions are discussed next.

Region I

Optical observations of test specimens during cyclic loading revealed that cracks initiated at the outer surface of the composites at about the same number of cycles as that for the matrix without any reinforcement; the strain level remained equal to 0.65%. SEM fractographic studies further revealed two distinct zones in the fractured surfaces of the fibers: fatigue failure and tensile failure portions, as are expected for a ductile reinforcement.[7] Also observed were a few secondary cracks in the matrix, in addition to a primary crack dominating others and finally causing the failure of the composite.

The proposed mechanism is as follows: At low fiber volume fractions, the effect of reinforcement is negligible in enhanc-

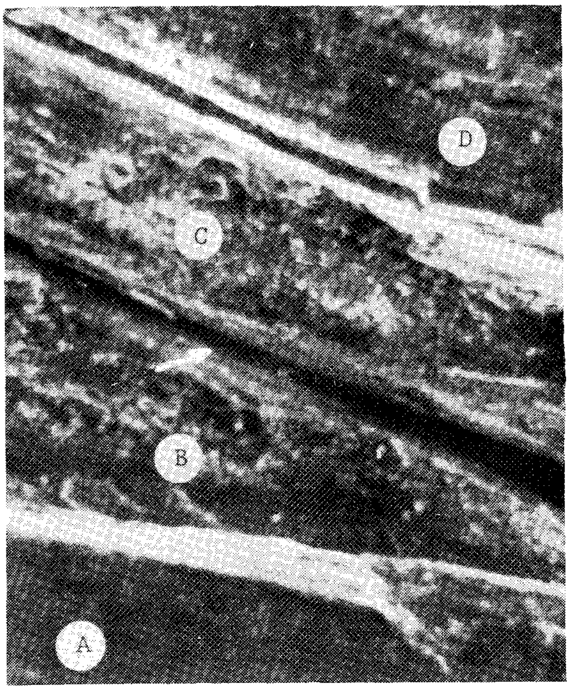

Fig. 6 Matrix delamination at high fiber volume fractions. A, B, C, D are fibers.

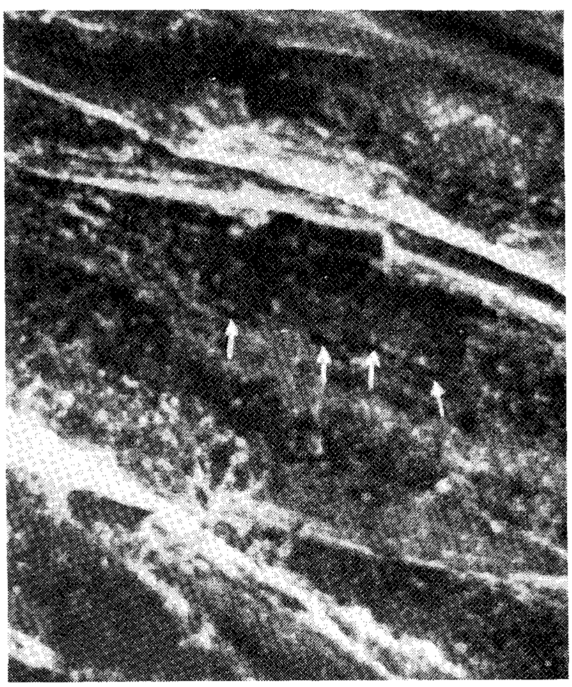

Fig. 7 Longitudinal crack in a fiber at high fiber volume fractions.

ing the fatigue life of composites because the fibers do not appreciably reduce the matrix stress, do not inhibit the crack growth once it has started, and, since they are themselves partially fatigued, they fail immediately due to sudden increase in stress level after the failure of the matrix.

Region II

In composites having medium range of fiber volume fraction, early cracks were found to initiate at the outer surface of the specimens at about the same or slightly lower number of cycles than that for the unreinforced matrix specimens. SEM fractographs further revealed a large number of microcracks in the matrix portion in composites. A few secondary cracks and a primary crack were observed in fibers (see Fig. 5). Matrix striations[35,37] were observed near the interface, as can be seen in Fig. 5. In addition, limited matrix delamination adjacent to the interface was found to cause separation of a few fibers. Based on these observations, the following micromechanisms are proposed for the enhanced fatigue life of the composites in this region of medium fiber volume fraction.

Reinforcement plays a dominant role in contributing to high fatigue resistance of composites compared to a nominal contribution of the matrix. As the fiber volume fraction increases, the fatigue resistance of the fibers increases because of reduced effective stress level in them and their enhanced capability in crack shielding. On the other hand, fiber/matrix interface, relatively stronger than the matrix, contributes to high fatigue resistance of the composites by branching many cracks in the matrix in the transverse direction and a few in the longitudinal direction parallel to the fibers by causing the matrix to delaminate adjacent to it without causing its own failure. The final fractures of the specimen are caused by a sudden link-up of most of the transverse cracks and the consequential failure of the already severely fatigued fibers under increased tensile stress.

Region III

In this region of high fiber volume fraction, too much matrix delamination was observed (see Fig. 6), leading to a downward trend in fatigue life of the composites. In addition to the fracture processes mentioned in region II, a longitudinal crack inside a fiber was also observed in SEM studies (see Fig. 7). The proposed mechanisms in this region are described below.

The fatigue failure of composites becomes very chaotic. As the fiber volume fraction increases, the matrix finds itself unable to transfer loads to the fibers because of reduced interfiber distance. This leads to premature failure of the matrix and to severe stress concentrations at certain fibers, thereby causing them to fail immediately. This in turn leads to an overall very nonuniform stress distribution causing further sudden breakage of other fibers along with their longitudinal separation.

From the preceding, it is obvious that interest in composites having high fatigue resistance lies in the medium fiber volume fraction range. It should be recalled here that all the composites tested under cyclic loading have an interface relatively stronger than the matrix and have maximum tensile strengths. Tensile strength results of composites fabricated under conditions identical to those of fatigue specimens are presented in Table 5. Included in this table are fatigue life data obtained from Eq. (3) and fatigue life to tensile strength ratios. It is remarkable to see an order of magnitude increase in fatigue resistance capability of composites over that of the matrix in terms of cycles to fracture/UTS ratio. Thus the basic goal of increasing the fatigue resistance capability of composites without compromising with their tensile strength has been achieved.

Conclusions

An optimum combination of hot pressing conditions such as 800 K, 1 min, and 140 MNm^{-2} has been established for the fabrication of stainless steel wire-reinforced aluminum matrix composites having fiber volume fractions ranging from 5% to 56%. A statistically valid logarithmic relationship between the low cycle fatigue life of the composites and their fiber volume fraction has been developed. The potential micromechanisms involved in low cycle fatigue fracture of the composites in low, medium, and high fiber volume fraction regions have been identified to be different. Fatigue resistance capability, in terms of a ratio of fatigue life to tensile strength, has been found to be enhanced for composites having a fiber/matrix interface relatively stronger than the matrix. In such composites, crack propagation is more dominant over crack initiation in controlling fatigue fracture of the composites.

References

[1]*Metal Matrix Composites: Status and Prospects,* National Materials Advisory Board, National Academy of Sciences, Washington, D.C., NMAB-313, 1974, pp. 1-105.

[2]Signorelli, R.A., "High-Temperature Composites—Status and Future Directions," *Progress in Science and Engineering of Composites,* edited by T. Hayashi, K. Kawata, and S. Umekawa, Vol. 1, ICCM-IV, Tokyo, 1982, pp. 37-48.

[3]Signorelli, R.A., "Metal Composites for Aircraft Propulsion Systems," *Proceedings of the 1975 International Conference on Composite Materials,* edited by E. Scala, E. Anderson, I. Toth, and B.R. Noton, Vol. 1, ICCM-I, Geneva, 1975, pp. 411-431.

[4]O'Lone, R., "Airframe Makers Eye New Turboprops," *Aviation Week & Space Technology,* Vol. 116, June 28, 1982, pp. 73-88.

[5]Steine, J.E., "How Decisions are Made," AIAA Paper, Wright Brothers Lecture in Aeronautics, Aug. 1982.

[6]Metcalfe, A.G., "Fiber-Reinforced Titanium Alloys," *Composite Materials,* edited by L.J. Broutman and R.H. Krock, Vol. 4, Academic Press, New York, 1974, pp. 269-318.

[7]Toth, I.J., "Creep and Fatigue Behavior of Unidirectional and Cross-Plied Composites," *Composite Materials: Testing and Design,* ASTM STP 460, 1969, pp. 236-253.

[8]Salkind, J.J., "Fatigue of Composites," *Composite Materials: Testing and Design,* ASTM STP 497, 1972, pp. 143-169.

[9]Hancock, J.R., "Fatigue of Metal-Matrix Composites," *Composite Materials,* Vol. 5, edited by L.J. Broutman and R.H. Krock, Academic Press, New York, 1974, pp. 371-414.

[10]Amateau, M.F. and Hanna, W.D., "Fatigue Behavior of Aluminum Alloy-30% Graphite Fiber Composites," *Proceedings of the 1975 International Conference on Composite Materials,* Vol. 1, edited by E. Scala, E. Anderson, I. Toth, and B.R. Noton, ICCM-I, Geneva, 1975, pp. 586-601.

[11]Stinchcomb, W.W. and Reifsnider, K.L., "Fatigue Damage Mechanisms in Composite Materials: A Review," *Fatigue Mechanisms,* edited by J.T. Fong, ASTM STP 675, 1979, pp. 762-787.

[12]Shimizu, H. and Dolowy, J.F. Jr., "Fatigue Testing and Thermal-Mechanical Treatment Effects on Aluminum-Boron Composites," *Composite Materials: Testing and Design,* ASTM STP 460, 1969, pp. 192-202.

[13]Hancock, J.R., "Fatigue of Boron-Aluminum Composites," AFML-TR-72-113, 1972, pp. 1-34.

[14]Toth, I.J. and Shimmin, R.D., "Fatigue and Fracture of Metal-Matrix Composites," AFFDL-TR-70-144, 1970, pp. 343-376.

[15]Menke, G.D. and Toth, I.J., "The Time Dependent Mechanical Behavior of Composite Materials," AFML-TR-70-174, 1970, pp. 1-40.

[16]Kreider, K.G. and Prewo, K.M., "Boron-Reinforced Aluminum," *Composite Materials,* Vol. 4, edited by L.J. Broutman and R.H. Krock, Academic Press, New York, 1974, pp. 399-471.

[17]Baker, A.A., Braddik, D.M., and Jackson, P.W., "Fatigue of Boron-Aluminum and Carbon-Aluminum Fiber Composites," *Journal of Materials Sciences,* Vol. 7, 1972, pp. 747-762.

[18]Varschavsky, A. and Tamayo, P., "The Cyclic Stress Behavior of a 355 Stainless Steel 2024-T8 Aluminum Alloy," *Journal of Materials Sciences,* Vol. 4, 1969, pp. 653-657.

[19]Toy, A., "Mechanical Properties of Beryllium Filament-Reinforced Aluminum Composites," *Journal of Materials,* Vol. 3, 1968, pp. 43-58.

[20]Petrasek, D.W. and Signorelli, R.A., "Tungsten Fiber Reinforced Super-Alloys—A Status Review," NASA TM 82590, 1981, pp. 1-67.

[21]Fleck, J.M., "Fabrication of Tungsten-Wire/FeCrAlY-Matrix Composites Specimens," TRW, Cleveland, Ohio, TRW Rept. ER-8076, 1979.

[22]Nilsen, N. and Sovik, J.H., "Fatigue of Tungsten Fiber Reinforced Nickel," *Proceedings of the Spring Meeting,* Institute of Metallurgists, London, 1974, pp. 851-854.

[23]Bhatt, R.T. and Grimes, H.H., "Fatigue Behavior of SiC Reinforced Ti (6Al-4V) at 650°C," *Metallurgical Transactions A,* Vol. 13A, 1982, pp. 1933-1938.

[24]Gouda, M.M., Prewo, K.M., and McEvily, A.J., "Mechanism of Fatigue in Boron-Aluminum Composites," *Fatigue of Fibrous Composite Materials,* ASTM STP 723, 1981, pp. 101-115.

[25]Hancock, J.R. and Shaw, G.G., "Effect of Filament-Matrix Interdiffusion on the Fatigue Resistance of Boron-Aluminum Composites," *Composite Materials: Testing and Design,* ASTM STP 546, 1974, pp. 497-506.

[26]Mileyko, S.T. and Anishchenkov, V.M., *Mekhanika Kompozitnykh Materialov,* (*Mechanics of Composite Materials*), 1980, pp. 409-417.

[27]Bhagat, R.B., "Investigation of the Fabrication of Stainless Steel Fiber Reinforced Aluminum Composites," Ph.D. Thesis, Dept. of Metallurgical Engineering, Indian Institute of Technology, Bombay, 1981.

[28]Bhagat, R.B. and Ramakrishnan, P., "Interfacial Interactions in Aluminum Matrix Stainless Steel Fiber Composites," *Progress in Science and Engineering of Composites,* Vol. 2, edited by T. Hayashi, K. Kawata, and S. Umekawa, ICCM-IV, Tokyo, 1982, pp. 1297-1305.

[29]Mazzel, P.J., Vandrunen, G., and Hakim, M.J., "Powder Fabrication of Fiber-Reinforced Superalloy Turbine Blades," *Advanced Fabrication Techniques in Powder Metallurgy and Their Economic Implications,* AGARD-CP-200, 1976, pp. SC 7-1 to 7-16.

[30]Bucci, R.J., "Selecting Aluminum Alloys to Resist Failure by Fracture Mechanisms," *Engineering Fracture Mechanics,* Vol. 12, pp. 407-441.

[31]Gross, M.R., "Engineering Materials Evaluation by Reversed Bending," *Manual on Low Cycle Fatigue Testing,* ASTM STP 465, 1969, pp. 149-162.

[32]Gibbons, W.G., "Strain-Cycle Fatigue of 70-30 Copper Nickel," *Transactions of the American Society of Mechanical Engineers,* Series D, Vol. 88, 1966, pp. 552-554.

[33]Draper, N.R. and Smith, H., *Applied Regression Analysis,* John Wiley, New York, 1966.

[34]Gunst, R.F. and Mason, R.L., *Regression Analysis and Its Application,* Marcel Dekker, New York, 1980.

[35]Colangelo, V.J. and Heiser, F.A., *Analysis of Metallurgical Failures,* John Wiley, New York, 1974.

[36]Engel, L. and Klingele, H., *An Atlas of Metal Damage,* Wolfe, London, 1974 (German)/1981 (English), p. 86.