Japanese Aerospace Literature This month: *Crack Propagation*

A95-39501 Fatigue crack growth properties in SiC particulate-reinforced cast aluminum alloy composites. J. HU, S. KUMAI, A. SEKIKAWA, Y. HIGO (Tokyo Inst. of Technology, Yokohama, Japan), and S. NUNOMURA (Niigata Inst. of Technology, Kashiwazaki, Japan), *Japan Institute of Light Metals, Journal* (ISSN 0451-5994), Vol. 45, No. 6, 1995, pp. 309–314. In Japanese. 11 Refs. Documents available from Aeroplus Dispatch.

The effects of the volume fraction, solidification structure, and particle distribution on fatigue crack growth properties in SiC particulate-reinforced cast aluminum alloy composites have been investigated. Compared with the unreinforced matrix alloys, fatigue crack growth resistance of the cast composites is found to be improved in the low Delta K region, deteriorated at the high Delta K region, and comparable in the Paris region. These correspond to the crack growth behavior of the powder metallurgy-processed composites which exhibit fine matrix microstructure and homogeneous particle distribution. However, the fatigue crack growth characteristics of the cast composites are influenced by the solidification structure. The dendritic solidification structure including nonuniform particle distribution results in complicated crack growth paths, and the particle segregation provides both positive and negative effects for the fatigue crack growth properties. (Author)

A95-38089 Extremely sensitive dependence of strength after proof testing of ceramics on initial strength. M. ICHIKAWA (Univ. of Electro-Communications, Chofu, Japan), *Materials Science Research International* (ISSN 1341-1683), Vol. 1, No. 1, 1995, pp. 59–64. 15 Refs. Documents available from Aeroplus Dispatch.

It is shown in proof testing of ceramic components that the phenomenon that strength after proof testing, S(f), depends quite sensitively on initial strength, S(i), appears under certain conditions. For example, a slight difference of S(i) of only 0.005 MPa results in a large difference of S(f) of some 400 MPa. The reason and conditions for this phenomenon are investigated theoretically. It is shown that this phenomenon appears when the unloading stress rate is considerably low and the crack growth exponent n is large as in ceramics. Practical aspects of the phenomenon are also discussed. (Author)

A95-38085 Simulation of debonding on the interface and subsequent creep crack growth in the matrix for metal matrix composite. M. MIZUNO, K. TANAKA, and T. INOUE (Kyoto Univ., Japan), *Materials Science Research International* (ISSN 1341-1683), Vol. 1, No. 1, 1995, pp. 17–22. 13 Refs. Documents available from Aeroplus Dispatch.

The mode of debonding on the interface between Al matrix and SiC whisker aligned unidirectionally is simulated by using the finite element method, and the subsequent creep crack growth in the matrix at 300 C is treated in the framework of the continuum damage mechanics. To estimate damage and stress development in the vicinity of the whisker, a unit cell model based on a kind of periodic boundary condition is employed. Damage development associated with stress/strain for the unit cell model is calculated as the axisymmetric and also plane strain conditions, and the difference between the results is discussed. The analyses of debonding and creep crack growth are carried out by using a local approach, and macroscopic creep deformation of MMC as well as microscopic damage and stress distribution is evaluated, and the result is discussed in comparison with the experimental data.

A95-37296 On intelligent structures using optical fiber—Crack sensing with optical fiber. M. ZAKO, H. URAGAKI, and K. KODATE (Osaka Univ., Suita, Japan), *Japan Society of Materials Science, Journal* (ISSN 0514-5163), Vol. 44, No. 499, 1995, pp. 493–497. In Japanese. 7 Refs. Documents available from Aeroplus Dispatch.

Recently, many attentions have been paid to an optical fiber as a sensor for intelligent structures. In present study, the optical fiber is used as a crack sensor for mortar beam. The sensing properties have been investigated by three-point bending test. Fresnel reflection of four optical fibers, which have been stuck on the surface of mortar beam with epoxy resin, is observed with OTDR (Optical Time Domain Reflectometer). When progression of a crack occurs in the mortar, the crack or the crack propagation breaks the optical fiber. Therefore, the cracking point can be measured by Fresnel reflection. In addition, the crack propagation in the mortar beam can be also measured by the breaking sequence of four optical fibers. Hence, it has been recognized that an optical fiber by using OTDR is very useful as a crack sensor for intelligent structures. (Author)

A95-35436 An accelerated testing method of ZrO_2-based FGM coating for gas turbine blades. C. Y. JIAN, T. HASHIDA, H. TAKAHASHI (Tohoku Univ., Sendai, Japan), N. SHIMODA (Nippon Steel Corp., Chiba, Japan), and M. SAITO (Miyagi Prefectural Inst. of Technology, Japan), *FGM 94; Proceedings of the 3rd International Symposium on Structural and Functional Gradient Materials*, Swiss Federal Inst. of Technology, Lausanne, Switzerland, 1994 (A95-35401 09-23), Lausanne, Switzerland, Presses Polytechniques et Universitaires Romandes, 1995, pp. 419–424. 3 Refs. Documents available from Aeroplus Dispatch.

This paper presents the results of thermal shock and fatigue tests conducted on ZrO_2 thermal barrier coating systems under the simulated temperature environments of gas turbine blades. Cylindrical specimens of a conventional two-layer coating and a functionally gradient material (FGM) coating were tested. Acoustic emission (AE) monitoring was conducted to detect the fracture process of the coating systems. To determine an appropriate thermal load for an accelerated testing method, four different heating/cooling thermal cycles were used for the thermal shock and fatigue tests. The results of the temperature and AE measurements were used to determine the delamination growth during the fatigue tests, and the growth rate was used to evaluate the effects of heating rate and cooling rate on the fracture of the coating. Finally, a suitable thermal cycle for accelerated testing was determined. (Author)

A95-35412 Elaboration of symmetric functionally gradient materials of the Al_2O_3/TiC/Ni/TiC/Al_2O_3 system. Z. LI, K. TANIHATA and Y. MIYAMOTO (Osaka Univ., Ibaraki, Japan), *FGM 94; Proceedings of the 3rd International Symposium on Structural and Functional Gradient Materials*, Swiss Federal Inst. of Technology, Lausanne, Switzerland, 1994 (A95-35401 09-23), Lausanne, Switzerland, Presses Polytechniques et Universitaires Romandes, 1995, pp. 109–114. 8 Refs. Documents available from Aeroplus Dispatch.

Symmetric functionally gradient materials of the Al_2O_3/TiC/Ni/TiC/Al_2O_3 and Al_2O_3-30 wt% TiC/TiC/Ni/TiC/30 wt% TiC-Al_2O_3 were fabricated by SHS/HIP. Use of conventional additives such as MgO and Mo_2C were useful to control the gradual change of microstructures. Strong compressive residual stress as high as 200–300 MPa was induced in the outer layers due to the compositionally symmetric structures, resulting in remarkable reinforcement of mechanical properties of the outer ceramics. Moreover, new intelligent functions such as flaw tolerance and preferential crack propagation in a safe direction appeared. The symmetric gradient structure can create higher order functions than inherent material properties. (Author)

A95-35064 A consideration of evaluation of fatigue crack propagation rate from effective stress intensity factor range. C. MAKABE, H. KANESHIRO (Ryukus, Univ., Okinawa, Japan), S.-I. NISHIDA (Saga Univ., Japan), and H. SAKIHAMA (Japan Transocean Air Corp., Okinawa, Japan), *Journal of Testing and Evaluation* (ISSN 0090-3973), Vol. 23, No. 3, 1995, pp. 153–159. 22 Refs. Documents available from Aeroplus Dispatch.

The fatigue crack propagation law was investigated for the two cases of crack propagation in a region of welding residual stress and after overloading. In the former case, the crack propagation rate da/dN was found to depend on the stress ratio R defined by sigma(min)/sigma(max), where sigma (min), sigma(max) are the minimum and maximum cyclic stresses. Due to the tensile residual stress, the crack propagation rate increased as the stress ratio decreased in the range −2–0. In the latter case, the crack propagation rate da/dN after overloading was higher than that for the constant stress amplitude test at first and then became lower. The crack propagation rate was thus affected by both the residual stress and the overloading. However, the crack propagation behavior correlated well with the crack closure behavior. Therefore, in the cases considered here, the crack propagation law can be reasonably evaluated from the effective stress intensity factor range Delta-K(eff). (Author)

A95-32233 Subcritical interlaminar crack growth in fibre composites exhibiting a rising R-curve. A. OKADA (Nissan Motor Co., Ltd., Yokosuka, Japan), I. N. DYSON, and A. J. KINLOCH (Imperial College of Science, Technology and Medicine, London, United Kingdom), *Journal of Materials Science* (ISSN 0022-2461), Vol. 30, No. 9, 1995, pp. 2305–2312. 12 Refs. Documents available from Aeroplus Dispatch.

Subcritical crack growth behavior has been evaluated in composite laminates based on uniaxial carbon fibers in poly(ether-ether ketone) matrices. Double cantilever beam (DCB) specimens have been employed to give mode I loading, and it is shown that the materials exhibit a rising R-curve, i.e., the value of the interlaminar fracture energy increases as the crack propagates through the specimens. When a DCB specimen is held at a constant displacement, subcritical crack growth is found to occur. The velocity of the subcritical crack growth, v, has been measured using a load-relaxation technique. The relationships between v and the strain energy release rate are modelled using power-law expressions. Finally, it is considered that the R-curve behavior is most likely caused by fiber bridging which develops behind the crack tip as the delamination propagates through the specimen. Fiber bridging allows stress to be transferred across the crack faces, behind the advancing crack tip, and so results in a 'shielding' of the stress field at the crack tip from the applied stress. (Author)

A95-31708 Fatigue crack growth characteristic of extruded high strength Al-Zn-Mg-Cu-La system alloys with high stress corrosion cracking resistance. Y. KISHI (Nippon Inst. of Technology, Saitama, Japan), Y. HIROSE (Kanazawa Univ., Japan), I. TSUKUDA, S. NAGAI (Showa Aluminum Co., Sakai, Japan), and K. HIGASHI (Osaka Prefecture, Univ., Sakai, Japan), *Japan Society of Materials Science, Journal* (ISSN 0514-5163), Vol. 44, No. 497, 1995, pp. 207–212. In Japanese. 14 Refs. Documents available from Aeroplus Dispatch.

Fatigue crack growth tests on an extruded Al-8Zn-2.5Mg-1.2Cu-4La (wt %) alloy were carried out using CT specimens (TL orientation). Crack closure was examined by the unloading elastic compliance technique. The main results are as follows: 1) a higher stress ratio gives a faster crack growth rate for the same stress intensity factort range; 2) crack closure occurs at a stress ratio of 0.1, its degree increasing with decreasing stress intensity factor range; and 3) the fatigue crack growth resistance of the extruded Al-8Zn-2.5Mg-1.2Cu-4La alloy is nearly equal to that of the commercial 7075T6 alloy. (Author)

A95-30975 Effect of temperature on small fatigue crack growth in Ni-base superalloys. M. OKAZAKI, H. YAMADA (Nagaoka Univ. of Technology, Japan), and S.-I. NOHMI (Kawasaki Heavy Industries Co., Ltd., Akashi, Japan), *Japan Society of Materials Science, Journal* (ISSN 0514-5163), Vol. 44, No. 498, 1995, pp. 348–354. In Japanese. 11 Refs. Documents available from Aeroplus Dispatch.

Based on the measurement of crack opening/closing behavior, the effect of temperature on small fatigue crack growth behavior was investigated in three kinds of Ni-base superalloys at the temperature range of 873–1123 K, and compared with those of long crack properties. A polycrystalline alloy (CM247LC-CC), a directionally solidified alloy (CM247LC-DS), and a single crystal alloy (CMSX-2) at temperatures of 873, 1023, and 1123 K, were used in the investigation. It was found that the propagation resistance and the fatigue threshold of the long crack increased with temperature in all of the materials, in appearance. However, the long crack growth rates at three different temperatures were approximately represented by a unique curve, by taking account of temperature dependences, not only of the crack closure level, but also of the elastic modulus. On the other hand, the small fatigue crack growth resistance decreased with temperature, even when the crack closure phenomenon was taken into account. In addition, the small fatigue crack exhibited considerably higher growth rate than the long crack at a given effective stress intensity factor range, and grew even at a lower effective stress intensity factor range than the long crack threshold. Based on the results thus obtained and the chemical analysis near the crack propagation plane, the factors which lead to the lack of similitude in the propagation law between small and long cracks were also discussed. (Author)

A95-30974 Fatigue strength of bolts tightened in plastic region—Fatigue strength assurance in reusing. H. YAMADA, K. SARUKI, S. HOTTA (Toyota Central Research and Development Labs., Inc., Aichi, Japan), and T. KAHON (Toyota Motor Corp., Japan), *Japan Society of Materials Science, Journal* (ISSN 0514-5163), Vol. 44, No. 498, 1995, pp. 338–342. In Japanese. 12 Refs. Documents available from Aeroplus Dispatch.

In reusing, a bolt is repeatedly tightened and loosened. In this study, the reusing properties of a shank-elongation bolt and a thread-elongation bolt tightened in the plastic region were investigated from the viewpoint of fatigue strength. The fatigue tests were carried out on both types of bolts which were subjected to 10-cycle tightening in the plastic region. As a result, the 10-cycle tightening had little influence on the fatigue limit of the bolts. However, on the thread-elongation bolt, the microcracks (about 7 μ in length) appeared at the thread root after repeated tightening in the plastic region. Then, the fatigue limit of the cracked bolt was predicted by using the fracture mechanics method. The threshold stress intensity factor range (delta Kth) of the bolt material was determined from fatigue crack propagation tests with prestrained smooth specimens under a high stress ratio. The stress intensity factor range (delta K) of the thread root was calculated by using the equation for a single-edged crack without considering stress concentration. In this equation, the crack length, consisting of the actual and latent crack length, was used as the effective crack length. The fatigue limit predicted from the above-mentioned delta Kth and delta K agreed approximately with the fatigue limit of the cracked bolt. This prediction clarified that the microcracks of about 7 μ in length had little influence on the fatigue limit of the bolts and that the fatigue limit decreased when the crack length increased beyond 7 μ. (Author)

A95-26189 The environmental effect on cyclic fatigue behavior in ceramic materials. G. CHOI (National Research Inst. for Metals, Tsukuba, Japan) and S. HORIBE (Waseda Univ., Tokyo, Japan), *Journal of Materials Science* (ISSN 0022-2461), Vol. 30, No. 6, 1995, pp. 1565–1569. 24 Refs. Documents available from Aeroplus Dispatch.

To understand the environmental effects on cyclic fatigue, static and cyclic fatigue behavior was investigated in air and in vacuum for normally sintered silicon nitride and alumina. The cyclic fatigue lifetime in vacuum is considerably longer than that in air, indicating a remarkable stress corrosion cracking effect in the latter, especially in alumina. In addition, the cyclic loading effect in vacuum is almost the same in silicon nitride relatively insensitive to environmental effects and alumina susceptible environmental effects. From such results, it has been found that cyclic fatigue in air is approximately expressed as the superposition of pure cyclic loading effect, which is defined as cyclic loading effect in vacuum, and environmental effect. This relation was applied to some kinds of ceramics with different values of fracture toughness or different microstructures, and the results obtained were discussed. (Author)

A95-24222 Mechanical fatigue of epoxy resin. M. NAGASAWA, H. KINUHATA, H. KOIZUKA, K. MIYAMOTO, T. TANAKA, H. KISHIMOTO (Toyota Technological Inst., Nagoya, Japan), and T. KOIKE (Yuka Shell Epoxy Co., Ltd., Yokkaichi, Japan), *Journal of Materials Science* (ISSN 0022-2461), Vol. 30, No. 5, 1995, pp. 1266–1272. 13 Refs. Documents available from Aeroplus Dispatch.

In static bending fatigue tests, epoxy resins show practically no fatigue if the stress given to specimen is lower than a critical value, which is close to the bending strength of the specimen. In cyclic bending fatigue tests, on the other hand, the resins are easily fractured even though the stresses are far below the critical values. Some strain may be accumulated on the surface of specimen through cyclic deformations. However, the strain accumulated is reversible. If the specimen is allowed to rest, the strain disappears. If the strain reaches a critical value, an irreversible transition may be induced, probably in the arrangement of segments on the surface. A crack nucleus thus created may propagate and cause the final fracture of the specimen, following the fracture mechanics of elastic materials. The lifetime of epoxy resins under cyclic bending load is determined by the time required for creating a crack nucleus on surface. (Author)

A95-23559 Microstructure and fracture characteristic of Si_3N_4-ZrO_2(MgO) ceramic composite studied by transmission electron microscopy. B.-T. LEE, T. KOYAMA (Mitsubishi Material Co., Omiya, Japan), A. NISHIYAMA, and K. HIRAGA (Tohoku Univ., Sendai, Japan), *Scripta Metallurgica et Materialia* (ISSN 0956-716X), Vol. 32, No. 7, 1995, pp. 1073–1077. 17 Refs. Documents available from Aeroplus Dispatch.

The microstructure and fracture characteristics of a $Si_3N_{4\text{-}5}$ wt% ZrO_2 (wt% 5 MgO) composite were studied experimentally using transmission electron microscopy, scanning electron microscopy, and a micro-indentation fracture technique. ZrO_2 grains with an irregular shape have a tetragonal structure partially stabilized by MgO and play an important role as a sintering agent. Si_3N_4 grain boundaries have thin (about 1 nm) amorphous layers, but the Si_3N_4/ZrO_2 interfaces are directly bonded without any amorphous phase or any reaction compound. The main fracture mode is intergranular. High fracture toughening mainly results from microcracking, crack deflection, and crack bridging.

A95-23152 Cyclic fatigue crack growth of silicon nitride under a constant maximum stress intensity. G. CHOI (National Research Inst. for Metals, Tsukuba, Japan), *Journal of Materials Science Letters* (ISSN 0261-8028), Vol. 14, No. 4, 1995, pp. 241–243. 15 Refs. Documents available from Aeroplus Dispatch.

It is currently unclear whether contacts between crack surfaces result in accelerated crack growth through the wedging effect, or conversely, to retarded crack growth through the effect of crack closure for ceramic materials. An effort is presently made to elucidate the role of these effects on cyclic fatigue crack growth. It is determined that it is the contacts created on crack surfaces during cyclic loading that leads to retarded crack growth; a wedging effect leads to accelerated crack growth.

A95-23144 Microstructure and crack sensitivity of laser-fusion zones of Ti-46 mol% Al-2 mol% Mo alloy. A. HIROSE, Y. ARITA, and K. F. KOBAYASHI (Osaka Univ., Suita, Japan), *Journal of Materials Science* (ISSN 0022-2461), Vol. 30, No. 4, 1995, pp. 970–979. 9 Refs. Documents available from Aeroplus Dispatch.

Laser surface melting and laser welding were performed on Ti-46 mol pct Al-2 mol pct Mo, using a 2.5 kW CO_2 laser. Microstructures of the fusion zones were changed in the following way as the cooling rate increased: massive alpha2 + massive gamma + lamellar (alpha2 + gamma) yield massive alpha2 + massive gamma yield alpha2. In laser surface melting, a single-phase structure of alpha-2 was seen when the calculated average cooling rates between 1773 and 1273 K were above 4000 K/s. In laser welding, the microstructure of the fusion zones was mainly composed of massive alpha2 + massive gamma + lamellar. The hardness of the fusion zones increased with increasing cooling rate, and the single-phase structure of alpha2 showed hardness above 500 Hv. While all of the laser surface-melted zones included cracking, in laser welding, crack-free welds could be obtained at traverse speeds below 50.0 mm/s and pre-heating temperatures above 573 K. As a result, cracking was prevented by selecting optimum welding parameters. (Author)

A95-17494 Fatigue strength of silicon nitride ceramics at high temperatures. H. HOHJO, A. YAMADA, and K. SARUKI (Toyota Central R&D Lab., Inc., Aichi, Japan), *Japan Society of Materials Science, Journal* (ISSN 0514-5163), Vol. 44, No. 496, 1995, pp. 128–132. In Japanese. 13 Refs. Documents available from Aeroplus Dispatch.

Static and cyclic bending fatigue tests were carried out on two types of Si_3N_4 ceramics at high temperatures in air. The effect of the viscosity of grain-boundary phase on fatigue strength was investigated; experimental results show that the effect of stress cycling on fatigue strength varies depending upon the following three temperature levels in relation to the viscosity of the grain-boundary phase. In the temperature region below the softening point of the grain-boundary phase, the cyclic fatigue strength was lower than the static fatigue strength; this may be due to the acceleration of crack propagation rate by stress cycling. Very few specimens had fractured at 10 exp 7 cycles. The average flexural strength of these survival specimens was over 20% higher than the average static strength of virgin specimens at the same temperature. In the temperature region where the grain-boundary phase is softened, the cyclic fatigue strength was lower than the static fatigue strength. The longer experimental life in cyclic fatigue is attributed to the high loading rate, which generates smaller strain. (Author)