Japanese Aerospace Literature This month: *Fracture Mechanics*

A93-54750 Fracture mechanics of high performance materials for severe environments. KAZUMI HIRANO, and TAKAYUKI SUZUKI, *Proceedings of the 2nd Symposium, Basic technologies for future industries—High-performance materials for severe environments,* Tokyo, Japan, Nov. 28, 29, 1991 (A93-54726 24-23). Tokyo, Japan Industrial Technology Association, 1991, pp. 185–191. 7 Refs. Documents available from AIAA Technical Library (IAA9324).

Fracture mechanics testing methodologies were developed in order to establish the material design concepts of high-performance materials for ultrahigh temperature environments. We have already developed the basic technologies for measuring and evaluating the fundamental mechanical properties up to 2000 C in a vacuum and inert gas environments. In this paper, high temperature fracture properties are evaluated for intermetallic compounds TiAl on the basis of fracture mechanics and electron microfractography.

A93-54317 Determination of stress intensity factor for orthotropic material by the method of caustics. GANX SO and SUSUMU TAKAHASHI, *Japan Society of Mechanical Engineers, Transactions A* (ISSN 0387-5008), Vol. 59, No. 562, June 1993, pp. 1526–1531. 13 Refs. Documents available from AIAA Technical Library (IAA9323).

The caustics method for estimating the stress intensity factor K of two-dimensional cracks has been investigated theoretically and experimentally, and provides a technique for easily obtaining the value of K. However, relatively few theoretical and experimental analyses for orthotropic material using this method have been conducted. In this paper, the optical method of caustics is extended to evaluate the stress intensity factor K for an orthotropic material theoretically and experimentally, and the range of applicability of this method is clarified. In this study, we make a comparison between the orthotropic and anisotropic material, and a plate of 'fiber reinforced plastics' is used.

A93-54175 Interfacial debonding between fiber and pre-cracked coating layer. SHOJIRO OCHIAI and MASAKI HOJO, *JIM, Materials Transactions* (ISSN 0916-1821), Vol. 34, No. 6, June 1993, pp. 563–568. Research supported by Iketani Science and Technology Foundation. 10 Refs. Documents available from AIAA Technical Library (IAA9323).

Energy release rate for static interfacial debonding between fiber and the pre-cracked coating layer was calculated with the aid of the shear lag analysis technique. Main results are summarized as follows. The energy release rate is high when the coating layer is thick, the Young's modulus of the fiber is low and that of coating layer is high. The debonding grows gradually or rapidly depending on the elastic moduli of the fiber and the coating layer, debonding length and thickness of the coating layer. The ratio of energy release rate for debonding in mode II to that for crack propagation into fiber in mode I is approximately 0.3, being independent of thickness of coating layer and difference in elastic moduli between fiber and coating layer.

A93-54124 Effect of hydrogen charge on Charpy impact energy in Ti-15V-3Cr-3Al-3Sn and Ti-13V-11Cr-3Al alloy. KEIJIRO NAKASA, HIROSHI SATOH, and HUMITAKA NISHIYAMA, *Japan Institute of Metals Journal* (ISSN 0021-4876), Vol. 57, No. 6, June 1993, pp. 637–644. 18 Refs. Documents available from AIAA Technical Library (IAA9323).

Charpy impact tests were carried out on the Ti-15V-3Cr-3Al-3Sn (15-3-3-3) and Ti-13V-11Cr-3Al (13-11-3) alloys which were hydrogen-charged in sulfuric acid solution with a concentration of 0.5 kmol/cu m under a charging current density of 1000 A/sq m. Hydrogen charging resulted in a decrease in Charpy impact energy for the as-solution treated 15-3-3-3 alloy at temperatures lower than 300 K, and for the aged alloy at temperatures lower than 700 K. For the aged 13-11-3 alloy, the impact energy decreased slightly by hydrogen charging at all testing temperatures. The aged 15-3-3-3 alloy was higher in hydrogen concentration C(H) than the as-solution treated one and the aged 13-11-3 alloy, and the alloys did not show any change in C(H) by heating up to 700 K. The hydrogen charging promoted the cleavage fracture of the as-solution treated 15-3-3-3 alloy and the aged 13-11-3 alloy, and the quasi-cleavage fracture of the aged 15-3-3-3 alloy.

A93-54123 Effect of oxygen on deformation behavior of texture controlled titanium. YONOSUKE MURAYAMA, MASATO MIKAMI, SEISHI ISHIYAMA, and SHUJI HANADA, *Japan Institute of Metals Journal* (ISSN 0021-4876), Vol. 57, No. 6, June 1993, pp. 628–636. 15 Refs. Documents available from AIAA Technical Library (IAA9323).

Mechanical properties of alpha Ti are strongly influenced by texture and oxygen content. The effect of texture and oxygen content on the deformation behavior was investigated using three kinds of textured Ti sheets containing 0.05, 0.1, 0.2, and 0.4 mass pct O. Especially, we paid attention to deformation twinning and the c+a line slip. Consequently, it was found that the occurrence of deformation twinning is suppressed and c+a line dislocations become operative as the oxygen content increases. Therefore, anisotropy in mechanical properties due to the deformation twinning disappears as the oxygen content increases. However, the operation of the c+a line slip having high critical resolved shear stress leads to easy cleavage fracture and reduced elongation.

A93-53792 Effect of fiber orientation on the compressive dynamic strength of unidirectionally reinforced carbon/epoxy composites. TOSHIO JINGU, *Japan Society of Mechanical Engineers, Transactions A* (ISSN 0387-5008), Vol. 59, No. 560, April 1993, pp. 1120–1125. 10 Refs. Documents available from AIAA Technical Library (IAA9323).

The strength of unidirectionally reinforced carbon/epoxy composites (CFRP) subjected to the compressive impact load was measured by the split Hopkinson pressure bar method (SHPBM), then the effect of fiber orientation on the compressive impact strength was investigated. Stress of the specimen, caused by multiple reflected stress waves at its ends in contact with the incident bar and transmitter, was analyzed based on one-dimensional stress wave theory. The resulting formulation can be used to evaluate either the linear or nonlinear stress strain relation. The strength of a specimen of zero-degree fiber is the greatest. The strain of a specimen of 45-degree fiber is the largest. A split fracture parallel to the fiber appeared in the specimen of zero degree fiber. Inclination of the fracture surface of specimens of 30-, 45-, and 60-degree fiber is in alignment with the fiber orientation. That of 90 degrees is not. The impact strength is about 80 MPa larger than the static strength. In contrast, the dynamic elongation is smaller than the static elongation.

A93-53787 Fracture analysis of whisker-reinforced aluminum alloys. MASANORI KIKUCHI, MAMTIMIN GENI, and KAZUMI HIRANO, *Japan Society of Mechanical Engineers, Transactions A* (ISSN 0387-5008), Vol. 59, No. 560, April 1993, pp. 1017–1023. 13 Refs. Documents available from AIAA Technical Library (IAA9323).

The fracture process of whisker-reinforced aluminum alloys is studied. First, tensile tests are carried out on specimens of various orientations. Dimple fracture occurs at the edge of the whisker fiber due to the stress concentration. It is also found that delamination occurs at the whisker matrix interface in the T-specimen. Then the fracture process is simulated by FEM. For the constitutive equation, Gurson's yield function is used. Void volume fraction is used as a fracture parameter and a conventional fracture analysis is carried out. Numerical results qualitatively agree with those of experiments. The delamination effect between the base metal and the whisker fiber is considered. It is concluded that the effect of the delamination is very small before fracture of the specimen.

A93-51126 Torsion of a transversely isotropic cylinder containing a penny-shaped crack. TAKAO AKIYAMA, TOSHIAKI HARA, TOSHIKAZU SHIBUYA, and TAKASHI KOIZUMI, *Japan Society of Mechanical Engineers, Transactions A* (ISSN 0387-5008), Vol. 59, No. 557, Jan. 1993, pp. 37–42. 18 Refs. Documents available from AIAA Technical Library (IAA9322).

This paper considers the axisymmetric problem for a transversely isotropic cylinder containing a penny-shaped crack. Expressing the stress component along the crack plane as an appropriate series, the problem is reduced to the solution of an infinite system of simultaneous equations. The displacement and stress distribution around the crack tip are shown graphically for various magnitudes of the crack diameter. It is shown that the stress intensity factor is independent of the transverse isotropy of the cylinder under constant torque.

A93-47363 Evaluation system for buckling of laminated composite cylindrical shells. HIROSHI OHYA and RINA OIKAWA, *Ishikawajima-Harima Engineering Review* (ISSN 0578-7904), Vol. 33, No. 3, May 1993, pp. 169–173. 25 Refs. Documents available from AIAA Technical Library (IAA9319).

An evaluation system was developed to calculate the design buckling loads of laminated composite cylindrical shells. The buckling problems of laminated composite cylindrical shells under axial compression, lateral pressure and hydrostatic pressure loadings were solved based on Fluegge equations. The buckling loads under bending were obtained assuming that the maximum critical bending stress is equal to the critical stress under axial compression. The reduction factors proposed in the NASA space vehicle design criteria to account for the differences between the calculated and the experimental buckling loads are adopted to calculate the buckling loads for design. The calculated results from the system were compared with the experimental values demonstrating the validity of the new system.

A93-47362 Experimental and analytical studies on impact loading damage in CFRP laminate. TADASHI NATSUMURA, HARUO ISHIKAWA, and TAKASHI KOIMAI, *Ishikawajima-Harima Engineering Review* (ISSN 0578-7904), Vol. 33, No. 3, May 1993, pp. 164–168. 7 Refs. Documents available from AIAA Technical Library.

An experimental investigation was conducted to estimate the impact damage area and the residual compressive strength of CFRP (Carbon Fiber Reinforced Plastics) laminates under penetrative impact loading. Stacking sequences of the laminates were simplified based on typical aero-engine blades or vanes for design reference. The effects of impact velocity and stacking sequence of the laminates on the damage area and the residual compressive strength were investigated. Numerical simulations were also conducted to estimate impact failure mechanisms. Some methodologies for impact resistance design are discussed.

A93-53832 Studies on fracture mechanisms of Class A-SMC Composites by means of acoustic emission monitoring—Effects of fiber and filler contents. MEGUMU SUZUKI, SOTOAKI KIDA, AMAYUKI OHTA, YOSHIHIRO KATOH, and HISANORI MIYASHITA, *Japan Society of Mechanical Engineers, Transactions A* (ISSN 0387-5008), Vol. 59, No. 561, May 1993, pp. 1306–1312. 9 Refs. Documents available from AIAA Technical Library.

The fracture mechanisms of Class A-SMC (Sheet mold compound) composites with various contents of fiber and filler are studied by AE monitoring. It is found that the loads of Pb and Pc at the inflection points of the total AE energy curve determined by means of the energy gradient method are in good agreement with the loads determined by means of the SIF method. The loads increase with an increase in the fiber content and show values near or equal to the maximum at 160 phr of the filler content. The damage of constituents at the loads are deduced from the AE amplitude distribution and the frequency analysis. The effects of the fiber and filler contents on damage initiation and growth are confirmed on the notch tip at the loads by means of the ink staining method.

A93-53784 Effects of submicro structural parameter for crack propagation resistance in epoxy resin. KAZUO OGAWA, AKIHIRO MISAWA, MASAHISA TAKASHI, and TAKESHI KUNIO, *Japan Society of Mechanical Engineers, Transactions A* (ISSN 0387-5008), Vol. 59, No. 560, April 1993, pp. 890–895. 10 Refs. Documents available from AIAA Technical Library (IAA9323).

For the purpose of establishing an integrated explanation of fracture mechanism in the material, the authors have discussed several features of crack growth threshold in an epoxy resin which shows remarkable time- and temperature-dependent mechanical behaviors. Namely, using a wide strip specimen having a long (semi-infinite) crack perpendicular to the free edge, slow and stable crack growth behavior was carefully observed under a constant rate of displacement and several temperatures over the viscoelastic range of the material. Then the time- and temperature-independent crack growth resistance was successfully obtained from crack growth curves and an extended J-integral for a linearly viscoelastic material. Minute fracture surface roughness was measured quantitatively with a double-beam interference microscope. The characteristic feature of the fracture surface was seen in the neighborhood just ahead of the initial crack front. Taking the temperature and rate dependent mobility of molecular entanglement around the moving crack front into account, some features of the submicroscopic mechanism of crack growth in this type of material are discussed.

A93-53783 Effect of anisotropy on fatigue properties of notched CFRP laminates. RI-ICHI MURAKAMI, KEISI YAMANAKA, TATSUICHI INABA, HIROSHI TAKAICHI, and MUNEAKI SHIBAYAMA, *Japan Society of Mechanical Engineers, Transactions A* (ISSN 0387-5008), Vol. 59, No. 560, April 1993, pp. 883–889. 12 Refs. Documents available from AIAA Technical Library (IAA9323).

The effect of anisotropy on fatigue properties of notched carbon fiber reinforced plastic laminates has been studied. The off-axis angle of carbon fiber was varied from 0 to 45 deg. The ultimate tensile strength and the tensile elastic modulus drastically decreased when the off-axis angle of carbon fiber increased to 30 deg. When the-off axis angle of carbon fiber increased over 30 deg, these values approached approximately constant values. The maximum tensile strain also increased and saturated to a constant value when the off-axis angle of the carbon fiber increased. The fatigue strength of notched CFRP laminates showed a similar dependence of ultimate tensile strength on the off-axis angle. The decrease of fatigue strength results from the fatigue damage in relation to the off-axis angle. The fatigue damage process was analyzed in terms of AE measurement and fractography. These results indicate that the fatigue damage process of CFRP laminates was significantly affected by the off-axis angle of carbon fiber.

A93-47361 Interlaminar fracture toughness of CFRP laminates. ITON CHOU, ISAO KIMPARA, KAZURO KAGEYAMA, and ISAMU OHSAWA, *Ishikawajima-Harima Engineering Review* (ISSN 0578-7904), Vol. 33, No. 3, May 1993, pp. 158–163. 10 Refs. Documents available from AIAA Technical Library (IAA9319).

This paper describes the effects of fiber orientations and moisture absorption of CFRP laminates on Mode I and Mode II interlaminar fracture toughness characterized by using standardized test methods. The remarkable R-curve characteristic appeared as the fiber orientation of CFRP laminates inclined to the propagating direction of delamination. The very front of delamination was only influenced by the moisture absorption of CFRP laminates.

A93-47358 Design guide for fine ceramic components. AKIHIKO SUZUKI and JYUN-ICHI HAMANAKA *Ishikawajima-Harima Engineering Review* (ISSN 0578-7904), Vol. 33, No. 3, May 1993, pp. 143–147. 11 Refs. Documents available from AIAA Technical Library (IAA9319).

Design guidelines are proposed to assure the safety and reliability of fine ceramic components operating under mechanical and thermal loads. The guidelines are intended to keep the fracture probability of components below a certain allowable level for fast fracture as well as time-dependent fracture. This is attained by a design formula incorporated in the guidelines which limits the maximum stresses of specific sections of the components to an allowable value. The guidelines also provide alternative design formulae for proof tested components to assess the effect of the proof test.

A93-51127 Statistical investigation of the fatigue life based on small-crack growth law. NORIO KAWAGOISHI, HIRONOBU NISITANI, MASAHIRO GOTO, TOSHINOBU TOYOHIRO, and SATOSHI KITAYAMA, *Japan Society of Mechanical Engineers, Transactions A* (ISSN 0387-5008), Vol. 59, No. 557, Jan. 1993, pp. 57–61. 23 Refs. Documents available from AIAA Technical Library (IAA9322).

Rotating bending fatigue tests were carried out on specimens of a 5052 Al alloy with two small blind holes, in order to investigate the distribution characteristics of the fatigue crack growth life based on the small-crack growth law dl/dN = C1(sigma super n sub a)l. The crack growth rate in each specimen was determined uniquely by (sigma super n sub a)l, therefore the crack growth life can be predicted by the small-crack growth law. On the assumption that the value of n is a fixed one and the value of C1 is a random variable, the distribution of the crack growth rate can be evaluated through the value of C3 in the relationship dl/dN = (C3)l. C3 follows a Weibull distribution approximately. The calculated distribution of the crack growth life based on the small-crack growth law and the distribution of C3 is in good agreement with the experimental results.

A93-43375 Stable crack extension of an alumina ceramic in three point bending tests. TAKETOSHI NOJIMA and OSAMU NAKAI, *Japan Society of Materials Science Journal* (ISSN 0514-5163), Vol. 42, No. 475, April 1993, pp. 412–418. 13 Refs. Documents available from AIAA Technical Library (IAA9317).

The use of three-point bending tests for determining the fracture toughness of engineering ceramics is complicated by the fact that, in these tests, the initial crack usually extends in an unstable manner. In the present study, three-point bending tests were carried out on alumina ceramic specimens in order to determine stability conditions for crack extension. A stability criterion for crack extension was obtained in terms of the Young's modulus, specimen thickness, and compliance of the testing machine. Based on the study, a crack stabilizer was designed, and stable crack extension tests were successfully performed on the alumina ceramic.

A93-43373 Effects of frequency and temperature on delamination crack growth of unidirectional CFRP under cyclic loading. YOSHIKAZU NAKAI, HIROFUMI YAMAMORI, MASAHARU NAKAMURA, and KIYOTSUGU OHJI, *Japan Society of Materials Science Journal* (ISSN 0514-5163), Vol. 42, No. 475, April 1993, pp. 384–390. 14 Refs. Documents available from AIAA Technical Library (IAA9317).

Double cantilever beam specimens of carbon fiber/epoxy laminates were tested in air at room temperature and 50 and 80 C to investigate the effects of temperature and frequency on the delamination crack growth under cyclic loading. At room temperature, the growth rate in terms of the number of cycles is found to be practically independent of the loading frequency. At 50 and 80 C, the growth rate, expressed in terms of the number of cycles, is found to increase at high temperatures and lower loading frequencies. However, when expressed in terms of time, the growth rate is found to be controlled by the maximum stress intensity factor and to be practically independent of the loading frequency at a constant temperature.

A93-40395 Characteristic of bending fracture in C/C composite—Effect of reinforcement fiber on fracture mechanism. H. KAWADA, Y. YAMAMOTO, T. YOSHIDA, I. OHTA, and I. HAYASHI, *Japan Society for Composite Materials Journal* (ISSN 0385-2563), Vol. 19, No. 2, 1993, pp. 72–78. 10 Refs. Documents available from AIAA Technical Library (IAA9316).

The objective of this paper is to reveal characteristics of bending fracture in C/C composites with two types of reinforcement (T300 and HTA, both PAN based high-strength type carbon fiber). Satin weave carbon fabric/carbon matrix laminates were fabricated, for which CFRP laminates were prepared with the hot press molding and then carbonized at about 1000 C. Both fibers have nearly the same mechanical properties. First of all, change of laminates thickness was investigated before and after the carbonization process. Three-point bending tests were carried out using specimens with various span/thickness ratios. Fracture surfaces and crack-propagation behaviors were characterized with a SEM.

A93-13639 Bulging of fatigue cracks in a pressurized aircraft fuselage. D. CHEN and J. SCHIJVE, *Aeronautical fatigue: Key to safety and structural integrity; Proceedings of the 16th ICAF Symposium,* Tokyo, Japan, Ma y 22-24, 1991 (A93-13626 02-39). Tokyo/Warley, United Kingdom, Ryoin Co., Ltd./Engineering Materials Advisory Services, Ltd., 1991, pp. 277–315. 26 Refs. Documents available from AIAA Technical Library (IAA9302).

Empirical and theoretical treatment are given to the bulging of fatigue-crack edges in pressurized aircraft fuselages to obtain data for full-scale fatigue testing. Experimental tests are undertaken to investigate sheet specimens under biaxial loading, curved sheets under tensile loads, and sheet specimens with large radii of curvature that are loaded with internal pressure. The nonlinear behavior of sheet curvature and bulging at the crack edge are studied analytically in terms of K-values, and these results are compared to FEM computations. Crack-edge bulging in pressurized Al-alloy sheet specimens is observed, and unfavorable effects on fatigue-crack propagation are confirmed. Crack-edge bulging is found to be nonlinear, and a biaxial tension field can reduce the bulging deformation. Predictions based on analytical relations are generally supported by the literature on cracks in fuselage structures, although the effect of the longerons should be included for more complete analyses.