Japanese Aerospace Literature
This month: *Fracture Mechanics*

A92-54272 The rigid bodies-spring models and their applications to three-dimensional crack problems. A. KIKUCHI, T. KAWAI, and N. SUZUKI, (Selected Papers from 2nd WCCM II—World Congress of Computational Mechanics, Universitaet Stuttgart, Germany, Aug. 27–31, 1990, A92-54242 23-39) *Computers & Structures* (ISSN 0045-7949), Vol. 44, No. 1–2, July 3, 1992, pp. 469–477, 479, 480.

This paper examines the practical application of the rigid-bodies-spring model (RBSM) as fashioned by Kawai et al. (1987) and Kikuchi et al. (1989) to the determination of fracture criteria. The theoretical basis of the method is reviewed giving a discrete 3D element that can lead to convergency of elastic solutions. The Mohr-Coulomb law is adopted for the yield criterion of the spring constants, and stable/dynamic crack propagation is treated with the RBSM. The method is employed numerically for a rectangular element consisting of five tetrahedral subelements. Potential fracture criteria are derived with the RBSM for the case of stable crack growth in an arbitrarily shaped initial crack. The extensive illustrations and numerical results compare favorably with experimental data showing that Mohr-Coulomb's law is more suitable than von Mises' for 3D crack problems.

A92-47297 Effect of alumina addition on bending fracture behavior in Y-PSZ. HARUSHIGE TSUBAKINO, MITSUHARU HAMAMOTO, KAZUNORI SONODA, and RYOICHI NOZATO, *Japan Society of Materials Science Journal* (ISSN 0514-5163), Vol. 41, No. 464, May 1992, pp. 631–636.

The bending fracture behavior of ZrO_2-3 mol pct Y_2O_3 (PSZ) containing 0 to 12 wt pct Al_2O_3 was studied with reference to the tetragonal-to-monoclinic phase transformation by three-point bending test, XRD, SEM-EDS, and dilatometry. PSZ fractured at the stress just over the elastic limit. In PSZ containing Al_2O_3, on the other hand, the plastic elongation and serration phenomena were clearly observed. The resulting fracture stress increased with the addition of Al_2O_3. The grain size and density were almost independent of the addition of Al_2O_3. The segregation of both Y_2O_3 and Al_2O_3 at grain boundaries was observed in PSZ containing Al_2O_3. The different fracture modes in PSZ containing Al_2O_3 could be attributed to this grain-boundary segregation phenomena. (Author)

A92-41780 Fracture behavior of a thermoplastic modified epoxy resin. A. MURAKAMI, D. SAUNDERS, K. OOISI, Y. YAMADA, T. YOSHIKI, M. SAITO, O. WATANABE, and M. TAKEZAWA, Proceedings of the 29th Symposium on Adhesion and Adhesives, Nagoya, Japan, June 20, 21, 1991, (A92-41776 17-27). Osaka, Adhesion Society of Japan, 1991, pp. 13–16.

Carbon fiber reinforced plastics for high elasticity and thermal resistance and low moisture absorption are discussed. The chemical structures of epoxy resins, thermoplastic modifier, and curing agent are described. Effects of resin composition on temperature and Young's modulus are given and test results on interlaminar fracture toughness are listed.

A92-39926 Bending strength of hydrogen-charged Ti-13V-11Cr-3Al alloy. KEIJIRO NAKASA, and JIANPING LIU, *Japan Institute of Metals Journal* (ISSN 0021-4876), Vol. 55, No. 9, Sept. 1991, pp. 922–927.

Bending tests were carried out on a Ti-13V-11Cr-3Al alloy which was charged with hydrogen by an electrolytic method and a high-temperature high-pressure H2 gas method. Bending strengths sigma(b) of as-solution treated specimens as well as aged specimens decreased with increase in electrolytic hydrogen charging time. The decrease in sigma(b) was small when the charging current density i(c) was 500 A/sq m, while it was large when i(c) were 1000 A/sq m and 3000 A/sq m. The bending strength of the specimens charged with hydrogen at high temperatures and high pressures decreased with increase in hydrogen concentration in specimens. X-ray diffraction analysis of the fracture surface showed that the decrease in sigma(b) by the hydrogen charging was caused by a decrease in cleavage strength of the (100) plane due to the resolution of hydrogen atoms into metal. (Author)

A92-39619 Matrix grain size effect and fracture behavior on bending strength and fracture toughness in multi-toughened Al_2O_3. K. IKEDA and T. KISHI, (Proceedings of the 16th Annual Conference on Composites and Advanced Ceramic Materials, Cocoa Beach, FL, Jan. 7–10, 1992, A92-39601 16-23) *Ceramic Engineering and Science Proceedings* (ISSN 0196-6219), Vol. 13, No. 7–8, July–Aug. 1992, pp. 164–171. Research supported by Japan Society for the Promotion of Science.

Al_2O_3 was reinforced with SiC-whisker and SiC-platelet as model material for multitoughening effect. All materials were fabricated by same procedure to neglect the effect of process difference. Grain size distribution was strongly affected by the shape and mass fraction of reinforcement, and the distribution changed fracture style in fracture surface. It was found that bending strength can be evaluated by Petch's law as first-order approximation. Compared with single-toughening composites, fracture toughness was highly improved in multitoughening composite. Deflection by platelet improved fracture toughness in case of fine matrix grain composites, and no interaction between whisker and platelet was observed. (Author)

A92-39011 Stabilized end notched flexure test—Characterization of mode II interlaminar crack growth. KAZURO KAGEYAMA, MASANORI KIKUCHI, and NOBORU YANAGISAWA, *Composite materials: Fatigue and fracture. Vol. 3* (A92-39001 16-39). Philadelphia, PA, American Society for Testing and Materials, 1991, pp. 210–225. Research supported by Agency of Industrial Science and Technology of Japan.

A stabilized end-notched flexure (ENF) test is proposed for experimental characterization of mode-II interlaminar crack growth. A special displacement gage is developed for direct measurement of crack-shear displacement (CSD) that is the relative shear slip between the upper and lower crack surfaces of the ENF specimen. The test is carried out under a constant CSD rate, ensuring that the crack growth is always stable. An analytical compliance method is applied successfully to the stabilized ENF test. Fracture toughness, GIIc, and crack length are calculated from the load-vs-CSD diagram by using the analytical relationship between crack length and CSD compliance. A computer-aided testing system is developed for continuous measurement of the crack length and fracture toughness. Fracture behavior of a unidirectional carbon/epoxy laminate is examined during crack propagation as well as at the crack initiation by applying the proposed protocol. (Author)

A92-37060 Impact damage analysis of aramid/glass hybrid laminates. TOSHIMITSU OHGAMI, ISAO KIMPARA, KAZURO KAGEYAMA, TOSHIO SUZUKI, and ISAMU OHSAWA, *Japan Society of Materials Science Journal* (ISSN 0514-5163), Vol. 41, No. 462, March 1992, pp. 382–388.

A numerical method for analyzing the dynamic strength of aramid/glass hybrid laminates is proposed and applied to estimate their multiaxial impact strength. The progressive fracture process under impact loading was well simulated and the numerical results showed close agreement with the experimental data, which exhibit brittle fracture. The fracture controlling process of mat/roving-cloth reinforced laminates is also discussed quantitatively on the basis of the present analysis.

A92-33871 Lamellar orientation dependent anisotropy of fracture toughness in gamma-base titanium aluminide. S. MITAO, T. ISAWA, and S. TSUYAMA, *Scripta Metallurgica et Materialia* (ISSN 0956-716X), Vol. 26, May 1, 1992, pp. 1405–1410.

The effect of lamellar orientation on the fracture toughness of a gamma-base titanium aluminide (Ti-47.2 percent Al) alloy was investigated. Results of standard fracture toughness tests and SEM observations showed that fracture toughness on the plane parallel to alpha-2/gamma lamellae was low (at about 10 MPa sq rt m), while that on the plane perpendicular to the lamellae was at around 35 MPa sq rt m. Fracture on the plane parallel to the lamellae is considered to be due to interlamellar separation.

A92-32765 Effects of fiber content on fracture mechanisms of short fiber reinforced PET composites. MEGUMU SUZUKI, SOTOAKI KIDA, MINORU SHIMBO, YASUSHI MIYANO, and SHIGERU MOROHASHI, *Composites; Proceedings of the 8th International Conference on Composite Materials* (ICCM/8), Honolulu, HI, July 15–19, 1991. Section 22–29 (A92-32535 13-39). Covina, CA, Society for the Advancement of Material and Process Engineering, 1991, pp. 27-H-1 to 27-H-9.

Effects of fiber content by volume on fracture mechanisms of short glass fiber reinforced PET(FRPET) composites are investigated by measuring the tensile strength, the parameters showing the adhesion between the fiber and the resin, and the fiber orientation in the composite materials. The results are verified by means of a frequency analysis of AE signals and microfractography. It is found that the tensile strength of FRPET increases with an increase in the fiber content at a fiber content lower than 17.3 percent (30 wt pct) but the rate of increase in the tensile strength seems to decrease slightly with an increase in the fiber content at a fiber content higher than 17.3 percent, and that the damage modes are changed from the resin cracking and the fiber debonding and pulling out, to the fiber debonding and pulling out and fiber breakage at a content of 17.3 percent.

A92-41786 Fracture behavior of adhesively bonded joints and spot welded joints in sheet metal joining. KIYOMI MORI, KATSURA FURUYA, TOSHIO SUGIBAYASHI, and MITOSHI KAI, Proceedings of the 29th Symposium on Adhesion and Adhesives, Nagoya, Japan, June 20, 21, 1991, (A92-41776 17-27). Osaka, Adhesion Society of Japan, 1991, pp. 73–76.

Experimental tests on spot welded joints in sheet metal joining are presented. The spot welded fracture stress is examined. Test results are analyzed.

A92-54554 The fracture behaviour of Vectran/epoxy quasi-isotropic laminates. ZEN-ICHIRO MAEKAWA, HIROYUKI HAMADA, TOMOHIRO KITAGAWA, and TOSHIHIKO OKUMURA, *Advanced Composites Letters* (ISSN 0963-6935), Vol. 1, No. 3, 1992, pp. 95–97.

Tensile behavior of quasi-isotropic liquid crystalline fiber reinforced composites were discussed. The fracture modes were observed by microscope and scanning electron microscope. As the result, initial fracture did not originate in 90 deg lamina, but in 45 deg lamina. (Author)

A92-55887 **Fracture behavior and fracture toughness of CeO2-stabilized ZrO2 under mixed mode loadings.** YASUO KOGO, YUTAKA KAGAWA, and HIROSHI HATTA, *Japan Institute of Metals Journal* (ISSN 0021-4876), Vol. 56, No. 7, July 1992, pp. 770–778.

Fracture toughness tests were conducted on specimens of CeO2-stabilized ZrO2 under mode I, mode II, and mixed-mode loading. It is found that the maximum principal stress criterion and the noncoplanar strain energy release rate criterion are applicable to the KI-KII fracture curve. Under mode II loading, the KIIC/KIC value is found to equal 0.6, which is lower that the value typically observed for nontransforming brittle materials. The observed low KIC/KIIC value is attributed to the shielding effect of the transformation which affects the mode I stress intensity only.

A92-52694 **Monte-Carlo simulation on notched strength of unidirectional boron-aluminum composites.** SHOJIRO OCHIAI and KOZO OSAMURA, *Journal of Materials Science* (ISSN 0022-2461)

The fracture behavior of center-notched unidirectional boron-aluminum composites is presently simulated via Monte Carlo methodology, under the assumption of quasi-self-similar notch extention. Notched strength is found to decrease with increasing notch size for a fixed width of specimen and with increasing specimen width for a fixed relative notch size. The various semiempirical failure criteria proposed in the literature could approximately describe the notched strength obtained by the present simulation under limited conditions, despite the difference in basic concept between those models and the method here employed. It is demonstrated that the characteristic lengths in several of the extant models have a strong positive correlation with damage zone size.

A92-51392 **Fracture toughness and transition of fracture behavior of silicon nitride at elevated temperatures.** NOBUYUKI MIYAHARA, YOSHIHARU MUTOH, KOHEI YAMAISHI, and TSUNEO OIKAWA, *Japan Society of Materials Science Journal* (ISSN 0514-5163), Vol. 41, No. 465, June 1992, pp. 892–898.

Fracture behavior in HIP-sintered silicon nitride at elevated temperatures was investigated using results of fracture toughness tests. It was found that the fracture toughness gradually decreased with increasing temperature up to 1200 C. Then, in the temperature range 1200-1275 C, a steellike brittle-to-ductile transition of fracture toughness was observed, where the fracture toughness rapidly increased from 4 MPa sq rt m to 8 MPa sq rt m.

A92-49785 **An elastic-plastic finite element analysis of a blunting interface crack with microvoid damage.** SHIGERU AOKI, KIKUO KISHIMOTO, and NORIYASU TAKEUCHI, *International Journal of Fracture* (ISSN 0376-9429), Vol. 55, No. 4, June 15, 1992, pp. 363–374. Research supported by MOESC and Martin Marietta Energy Systems, Inc.

A finite strain elastic-plastic finite element analysis is performed on a crack which lies on an interface between two dissimilar materials. The materials above and below the interface are assumed to be different from each other in yield stress or in strain-hardening exponent. Gurson's constitutive equation for porous plastic materials is used in order to take into account the effect of the microvoid nucleation and growth on the fields near the tip of a crack. It is found that the microvoids have larger effects on the crack tip blunting and stress fields for a bimaterial than for a homogeneous material. It is also found that the plastic strain and the microvoid volume fraction localize in a few narrow bands which grow into the softer material from the intersection of the interface and the blunted crack tip at inclinations of about 15 deg to 45 deg. (Author)

A92-48251 **Probability distribution of life times of stress corrosion cracking of 7075 aluminum alloy.** SHUHEI OHSAKI and TSUNEO TAKAHASHI, *Japan Institute of Light Metals Journal* (ISSN 0451-5994), Vol. 42, No. 5, May 1992, pp. 268–273.

Life time to stress corrosion cracking (SCC) of an aluminum alloy A7075-T6 in 3.5 percent NaCl solution or in pure water was measured under a stress along short transverse direction. SCC process is divided into crack initiation stage and crack propagation stage, and each stage is analyzed by the Weibull's distribution method. In NaCl solution the life time for each stage can be described by a composite Weibull's distribution. The shape parameter of mode 1 in the region with shorter life time is larger than unity, and that of mode 2 in the region with longer life time is close to unity. On the other hand, the life time in pure water follows a single Weibull's distribution with the shape parameter around unity. An average life time is smaller in NaCl solution than in pure water by a factor of two to four. In SCC process of mode 1 in NaCl solution, cracks nucleate at the intergranular corrosion pits. (Author)

A92-39851 **Electric potential CT method for measuring two- and three-dimensional cracks.** SHIRO KUBO, TAKAHIDE SAKAGAMI, and KIYOTSUGU OHJI, *Fracture mechanics* (A92-39843 16-39). London and New York, Elsevier Applied Science, 1991, pp. 235–254.

By applying the concept of inverse analysis, the electric potential computed tomography (CT) technique for measuring 2D and 3D cracks is presented. Based on the boundary element formulation, two inverse analysis schemes, i.e., the inverse boundary-integral equation technique and the least-residual technique, are developed for the determination of cracks from data of the electric potential observed on the surfaces of cracked bodies. It is shown by experiments and numerical simulations that the proposed method is useful for determining the size, shape and location of 2D and 3D cracks.

A92-47377 **Effect of laminated fracture on the low temperature absorbed energy in 5083 aluminum alloy.** YOSHIHIRO NAKAYAMA and TETSUYA TAKAAI, *Japan Institute of Light Metals Journal* (ISSN 0451-5994), Vol. 42, No. 4, April 1992, pp. 191–197.

The low-temperature toughness of 30-percent cold rolled and annealed 5083 aluminum alloy was studied with the Charpy impact test, and the effect of laminated fracture on the absorbed energy was investigated experimentally. Absorbed energy measured at 77 K was markedly increased by cold rolling. The increasing of the absorbed energy was due to increases in the fractured surface increased by the laminated fracture. Absorbed energy per unit area of the true fractured surface was decreased. Generation and propagation characteristics of the laminated fracture were enhanced by annealing treatment at 473 K for 60 ks. Laminated fracture, however, was reduced by annealing treatment at 523 K or 573 K. The effect of side grooves was to constrain the growth of laminated cracks in the vicinity of specimen ligament. Laminated fracture was observed across the specimen ligament in the specimens with side grooves. (Author)

A92-47201 **Thermomechanical behavior of thermal-stress relief type of functionally gradient material evaluated by differential temperature heating using H2/O2 combustion flame.** AKIRA KAWASAKI, ATSUSHI HIBINO, and RYUZO WATANABE, *Japan Institute of Metals Journal* (ISSN 0021-4876), Vol. 56, No. 4, April 1992, pp. 472–480.

A burner heating test for the thermomechanical evaluation of functionally gradient material in the laboratory is described. A temperature gradient is obtained by heating the ceramic side with a burner frame and cooling the metal side with water flow. The damage at the specimen surface is monitored with a microscope. A vertical crack formation at the ceramic surface is observed during the cooling cycle. The test temperature for the first crack formation is defined as a thermal barrier performance value for the test sample. It is found that the crack formation temperature is almost constant for the various samples and heating conditions, which indicates a strong dependency of the thermal barrier property on the material species. The crack formation mechanism is discussed on the basis of a thermal stress analysis using a finite element method. (Author)

A92-44659 **Fracture toughness of single crystal silicon at high temperatures.** KUNIO HAYASHI, SHINJI TSUJIMOTO, YASUNORI OKAMOTO, and TOMOZO NISHIKAWA, *Japan Society of Materials Science Journal* (ISSN 0514-5163), Vol. 41, No. 463, April 1992, pp. 488–494.

The fracture toughness K(Ic) on the major planes or single-crystal silicon was measured by the controlled surface flaw (CSF) and indentation fracture (IF) methods at high temperatures. The resulting K(Ic) values from the CSF method for the 100-, 110-, 111-, and 112-plane surface orientation of silicon up to about 500 C decreased with increasing temperature. In the low-temperature region, the linear decrease of K(Ic) for 110-, 111-, and 112-plane is explained on the basis of an elastic model. The K(Ic) values for 100-, 110-, 111-, and 112-planes of silicon increased rapidly over the temperatures of 500, 600, 700, and 800 C, respectively. It is found that the rapid K(Ic) increase for those plane at the individual critical temperatures is attributable to extensive plastic yielding in the vicinity of the crack tips relating the Schmid factor and numbers of slip systems for each plane. The K(Ic) values obtained by the IF method for 400-600 C were larger than those obtained by the CSF method for all planes.

A92-43106 **Coalescence criteria for coplanar multiple surface cracks.** TOSHIHIKO NISHIMURA and MIKIO SASAJIMA, Proceedings of the 28th Aircraft Symposium, Tokyo, Japan, Nov. 7–9, 1990, (A92-43095 18-01). Tokyo, Japan Society for Aeronautical and Space Sciences, 1990, pp. 72–75. Research supported by Japan Aircraft Development Corp.

New criteria are proposed to predict the coalescence for coplanar multiple surface cracks under uniform tensile loading. The coalescence is assumed to occur when the internal plastic zones between cracks are attached, or the brittle fracture condition is satisfied. The plastic zone sizes for the coplanar surface cracks are approximated using the Dugdale solution for the coplanar through cracks by empirically modifying the effect of the three-dimensional profile. The stress intensity factor of the multiple surface cracks is calculated based upon the Newman-Raju equation by multiplying the finite width and mutual interaction factors. The applicability of the proposed criteria is verified by correlating with the constant amplitude fatigue growth data. It is shown that the proposed coalescence criteria are superior to the ASME design rule. (Author)

A92-32821 **Failure modes and AE characteristics of carbon fabric composites.** FENG SUN, ISAO KIMPARA, KAZURO KAGEYAMA, TOSHIO SUZUKI, and ISAMU OHSAWA, *Composites; Proceedings of the 8th International Conference on Composite Materials* (ICCM/8), Honolulu, HI, July 15–19, 1991. Section 30–39 (A92-32535 13-39). Covina, CA, Society for the Advancement of Material and Process Engineering, 1991, pp. 31-C-1 to 31-C-10.

Static tensile failure behaviors and AE (acoustic emission) characteristics of non-notched and hole-notched carbon fabric composites was discussed in the present paper. Failure patterns of these composites were observed and then related to the AE parameters. The experimental results show that the arrangements and locations of failures were dependent on weave structures. It was concluded that the initiation and propagation of different failure modes could be evaluated by AE parameters and the behaviors of micro-failure modes of notched specimens were affected by stress concentration and hole size. (Author)