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Determination of Stress Intensity Factors and Fatigue Characteristics for Aluminium, Aluminium-Alumina Composite Material and Aluminium-Alumina FGM Specimens with Edge Crack by Simulation

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Abstract

Crack propagation studies Crack propagation studies on Functionally Graded Material (FGM) have been done using simulation techniques. Simulation of crack propagation has been done on an Isotropic Aluminium Single Edge Notch(Crack) Bend Test Specimen under Three Point Bend Test Conditions and also on three different compositions Aluminium-alumina composite specimen with single edge crack under Three Point Bend Test Conditions to estimate the K_I Stress Intensity Factor (SIF) for different initial crack length to depth ratios. Crack propagation studies on an Aluminium plate and Aluminium-alumina 15%, 20% and 25% composite plates under three point bend test conditions were done experimentally and the peak loads carried by these specimens have been used in simulation techniques. Simulation of crack propagation under three point bend test conditions has also been done on an Aluminium-alumina Functionally Graded Material (FGM). Estimation of K_I Stress Intensity Factors by simulation techniques has been done for Isotropic Aluminium, Aluminium-alumina composite and Aluminium-alumina FGM and the estimated K_I Stress Intensity Factor been compared between these three materials. Also compared are the induced von-mises stress and the maximum deflection of the specimens of these three materials obtained using simulation. Also the stress at the crack edge and the stress at the crack tip for the specimens of Isotropic Aluminium, Aluminium-alumina composite and Aluminium-alumina FGM have been obtained using simulation techniques and compared between these three materials.

Keywords-Aluminium-Alumina Composites and FGMs, Crack Propagation Studies, Crack-tip Stress Fields, Stress Intensity Factors, Three Dimensional Simulation Techniques

Introduction

Low-cost, light weight aluminium matrix composites have a good potential for application to aerospace structures [1]. Aluminium-Alumina isotropic composite is intended for applications involving high strength-to-weight requirements such as new drive shaft designs in automobiles and in advanced aircraft [2]. These composites that are stable at high temperatures and involve ceramics with high hardness have properties which facilitates production by easy casting techniques [3]. Mcdanels [1] has analysed the stress-strain, fracture and ductility behaviour of aluminium matrix composites containing discontinuous silicon carbide reinforcement and implies on the suitability of the low-cost, light weight aluminium matrix composites for application to aerospace structures. In applications involving severe thermal gradients, eg., thermal protection systems, FGMs exploit the heat, oxidation and corrosion resistance of ceramics and the strength, ductility and toughness of metals [4]. Marin [5] list out the fields of applications of the FGMs as thermal barrier coatings for space applications, nuclear fast breeder reactors etc. Literature is abundant with materials dealing with the manufacturability and characterization of the FGMs. Various powder processing technologies, viz. backward extrusion of Al-Al_3-Ti platelet particles by a centrifugal solid-particle method [6], a new solid free form fabrication technology, namely laser rapid forming (LRF) to fabricate bulk near-net-shape metallic based components [7], centrifugal casting technique to obtain materials with higher density on the outer regions of a casting due to applied centrifugal forces [8], Laser Cladding (LC)-based free-form fabrication technology which forms strongly bonded layers of fully dense and possibly homogeneous structures [9], the high velocity oxy-fuel (HVOF) combustion spray process combined with a computer controlled dual powder feed system and a powder injection arrangement allowing the simultaneous internal and external feeding of the constituent materials [10], multi-directional laser-based direct metal deposition, an additive manufacturing process to get the desired shape and orientation of the volume fraction of the constituent materials [11] are in use to produce the FGMs with the desired shape and orientation of the volume fraction of the constituent materials.

Tilbrook et al [12] used the finite element analysis to study the fracture behaviour of FGMs under flexural loading conditions. Li et al [13] have used the multiple isoparametric finite element method to obtain the mode I SIFs for FGM solid cylinders and found that the material property distribution affects the stress intensity factors to a great extent. The behaviours of embedded crack and external crack are different. Zhang and Paulino [14] investigated the dynamics of mixed mode fracture using cohesive zone modelling. It is found that the cohesive zone approach is effective in fracture evolution characteristics in homogenous and graded materials. Tilbrook et al [15] used finite element method to estimate crack-tip stress fields and propagation paths and compared with experimental results. Three dimensional finite element models have been used for the analysis of three dimensional cracks. Shim et al [16] used three dimensional finite element models to study the effect of material gradation on SIFs and K-dominance. Afsar et al [17] studied the problem of required material distribution to have the required fracture characteristic for an FGM cylinder. Afsar and Anisuzzaman [18] used a generalized method to obtain stress intensity factor of a thick-walled FGM cylinder. Hvizdos et al [19] experimentally studied the mechanical properties using indentation methods. Shock resistance using indentation quench method for an alumina/Zirconia FGM referred with the published literature.

The present paper deals with the three dimensional simulation models to study the fracture behaviour of single edge notch bend specimens under three point test conditions. The study compares the stress at the crack edge and the stress at the crack tip for the specimens of Isotropic Aluminum,, different aluminium-alumina compositions, viz. 85% aluminium-15 % Alumina, 80% aluminium-20 % Alumina, and 75% aluminium-25 % Alumina composite material specimens and aluminium-25% Alumina FGM with different initial crack lengths to depth ratios, obtained using simulation techniques.

Materials and Simulation Methods

The Simulation studies have been done on the materials, Isotropic aluminium, Aluminium-Alumina composite materials of three different compositions, viz. 85% aluminium-15 % Alumina, 80% aluminium-20 % Alumina, and 75% aluminium-25 % Alumina composite material and aluminium-alumina functionally graded material. In simulation study two points on the specimen was fixed as the same way as the experiments were carried out and the same load was given so as to compare the results effectively and to compare the suitability of aluminium-alumina FGM with isotropic aluminium and aluminium-alumina composite materials.

Specimens for Simulation

Simulation studies to determine the stress intensity factors have been done on models for Aluminium, Aluminium-Alumina composite materials of three different compositions, viz. 85% aluminium-15 % Alumina, 80% aluminium-20 % Alumina, and 75% aluminium-25 % Alumina composite material and aluminium-alumina FGM. The models use the elastic modulus values of the corresponding materials. In case of FGM the variation in the value of the elastic modulus for different layers of the specimen model is obtained using the Rule of mixtures. The models are created to simulate the experimental conditions. The specimen dimensions, initial crack lengths and the loads and the constraints applied are the same as that of the specimens used for the experiments.

Figure 1 shows the model Aluminium-Alumina 15% composite specimen of size 152 mm x 24 mm x 10 mm with an initial edge crack, fixed at the two points of gauge length 120 mm and loaded on the face opposite to the surface containing the edge crack, to simulate the three point flexural test conditions.

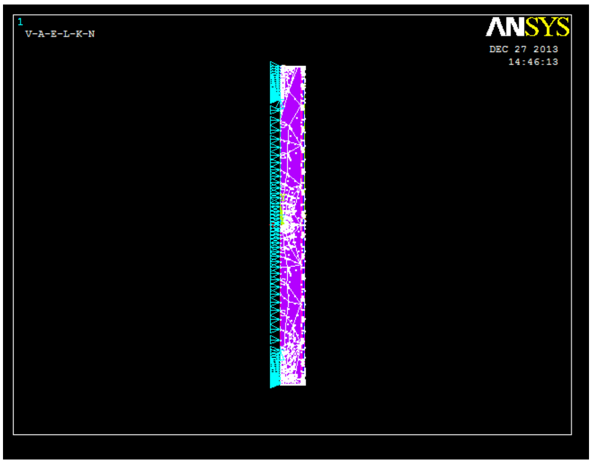

Fig. 1. Simulation model for Aluminum-Alumina 15% Composite Specimen with Initial Crack a/d ratio 0.1 with the loads and constrains applied.

Simulation Studies and Results

Macro programs have been developed to model the specimens to obtain the stress intensity factors using simulation techniques. Also the other desired results viz. the maximum von-mises stress induced in the specimen along with the maximum deflection are obtained using macro. The displacements and equivalent stresses induced at the start point of the crack at the edge of the plate and the crack tip also have been obtained using macro.

Preparation and the use of the macros for simulation techniques have enabled the simulation study to be conducted on many numbers of models. Recreating the models also become easier with the help of the macros. A sample portion of the macro used for aluminium-alumina FGM specimen with the Young's modulus value of 0.7 x 10^{11} N/m^2 for aluminum and 1.40 x 10^{11} N/m^2 for aluminium-alumina 25% has been reproduced below.

FINISH /CLEAR /input /prep7 et, 1, plane82,,, 2 et, 2, solid185 y=0.7e11 z= 1.4e11 y1=(0.75*y)+(0.25*z) y2=(0.5*y)+(0.5*z) y3=(0.25*y)+(0.75*z) MP, EX, 1, y MP, NUXY, 1, 0.3 MP, EX, 2, y1 MP, NUXY, 2, 0.3 MP, EX, 3, y2 MP, NUXY,, 0.3 MP, EX, 4, y3 MP, NUXY, 4, 0.3 MP, EX, 5, z MP, NUXY, 5, 0.3 l=152e-3 w=24e-3 d=10e-3 ratio=0.1 a=d*ratio gl=120e-3 p=a/400 q=3*a/4 r=a/8 s=gl/2 t=l/2 u=d+5e-4 v=u+5e-4 w1=v+5e-4 x=w1+5e-4 k, 1, 0, p k, 2, q, p k, 3, a, 0 k, 4, q,-1*p k, 5, 0,-1*p k, 6, 0,-1*s K, 7, 0,-1*t k, 8, d,-1*t k, 9, d, t k, 10, 0, t k, 11, 0, s k, 12, 0, p, w k, 13, q, p, w k, 14, a, 0, w k, 15, q,-1*p, w k, 16, 0,-1*p, w k, 17, 0,-1*s, w k, 18, 0,-1*t, w k, 19, d,-1*t, w k, 20, d, t, w k, 21, 0, t, w k, 22, 0, s, w k, 23, u,-1*t k, 24, u, t k, 25, u, t, w k, 26, u,-1*t, w k, 27, v,-1*t K, 28, v, t K, 29, v, t, w K, 30, v,-1*t, w K, 31, w1,-1*t K, 32, w1, t K, 33, w1, t, w K, 34, w1,-1*t, w K, 35, x,-1*t K, 36, x, 0 K, 37, x, t K, 38, x, t, w K, 39, x, 0, w K, 40, x,-1*t, w

The full length macro includes the commands that are used up to the point of obtaining all the desired results. For functionally graded materials additional four layers of 0.5 mm thickness (here it is depth) with varying mechanical properties were created using macros. The properties for different layers were obtained using the rule of mixtures. The value of Poisson's ratio has been kept at 0.3 for all the material specimens. For aluminium-alumina 25% composite material, Young's modulus value of 1.4 x 10^{11} N/m^2 has been used. Similarly for aluminium-alumina 15% composite material, Young's modulus value of 1.12 x 10^{11} N/m^2 and for aluminium-alumina 20% composite material, Young's modulus value of 1.26 x 10^{11} N/m^2 has been used. The properties for different compositions of aluminium-alumina composite material specimens were also obtained using the rule of mixtures, taking 0.7 x 10^{11} N/m^2 for aluminum and 3.50 x 10^{11} N/m^2 for alumina. The three modes of the Stress Intensity Factors(SIF) namely Mode I SIF, K_I, Mode II SIF, K_{II}, and Mode III SIF, K_{III} are obtained from simulations using Ansys 12. For a better comparison the stress intensity factors have been obtained for a uniform load of 5000 N across the different materials and different a/d ratios. Also the stress intensity factors have been obtained for the peak loads carried by the specimens with different a/d ratios.

Simulation Results and Discussions

The three modes of the Stress Intensity Factors (SIFs) namely Mode I SIF, K_I, Mode II SIF, K_{II}, and Mode III SIF, K_{III} are obtained from simulations using Ansys 12. Figure 2 plots the variation of the three SIFs with respect to different a/d ratios for the specimen model for the property values of Aluminium and aluminium-Alumina 15% material under 5000 N. The mode I SIF is predominant compared to the mode II SIF and the mode III SIFs. Mode I SIF shows the increasing trend with the increase in the a/d ratio.

For aluminium-Alumina 15% the values are no different from that of the aluminium specimen, because the SIFs are independent of the elastic modulus values. And is so for aluminium-Alumina 20% and aluminium-Alumina 25% material specimens. The change could be observed only in case of the FGMs were the different layers are modeled with different elastic modulus values.

Figure 3 plots the variation of the three SIFs with respect to different a/d ratios for the specimen modelled with the changing property values for aluminium-silicon carbide functionally graded material, Aluminium-Alumina FGM under uniformly applied load of 5000 N and for the different loads carried by the Aluminium-Alumina composite specimens in experimental studies. The predominance of Mode I SIF is observed in case of FGMs also. Both the mode II and the mode III SIFs are insignificant compared to the mode I SIF. Mode I SIF does not indicate any trend with the increase in the a/d ratio.

The Mode I SIF is very high and dominant in this case also and the Mode II and mode III SIFs keep low. Mode III SIF does not show any trend with increasing a/d ratio, though Mode II SIF shows an increasing trend. Here, Mode I SIF shows a decreasing trend with the increasing a/d ratio, obviously keeping in line with the decreasing experimental loads carried by the specimens with the increasing a/d ratios. In all the cases, under flexural loading conditions, the predominance of Mode I Stress Intensity Factor, K_I over the other two modes has been clearly established.

Figure 4 compares the mode I SIF, K_I and the mode III SIF, K_{III} between the different materials with initial crack lengths of different a/d ratios under uniform load of 5000 N. The predominant Mode I Stress Intensity Factor, K_I keeps fairly low in case of Aluminium-Alumina FGMs compared to that of the specimens of isotropic aluminium and the Aluminium-Alumina Composite materials, especially in case of increased initial crack lengths. Thus, the suitability of the FGMs to replace the aluminium or aluminium composite materials for aerospace structural applications is proved. Though, both the Mode II SIF, K_{II} and Mode III SIF, K_{III} keeps low compared to Mode I SIF, K_I, still these two SIFs also are very low in case of FGM compared against the other two materials, viz. aluminium and Aluminium-Alumina composite materials. Thus, all three modes of Stress Intensity Factors are comparatively very low in case of FGMs.

Figure 5 shows the compares the variation in the Von-mises stress and the maximum displacement induced at the crack tip region between the different materials and a/d ratios modelled under the uniform load of 5000 N across all the materials. The maximum stress induced around the crack-tip region is very low in case of FGMs compared against the other two materials, viz. aluminium and Aluminium-Alumina composite materials. Thus, in addition to all three modes of Stress Intensity Factors, the stress induced around the crack-tip region is also comparatively very low in case of FGMs. In line with the Stress Intensity Factors and the stress around the crack-tip region, the maximum deflection observed around the edge of the crack is also very low in case of FGMs.

Figure 6 shows the variation in the displacement and the stress observed at the crack-tip (invariably Node 4 in all the specimens), between the different materials and a/d ratios modeled under the uniform load of 5000 N. All three materials show a decreasing trend in the crack-tip displacement with increasing a/d ratio. Among the three materials compared, the displacement at the crack-tip is very low in case of FGMs.

The crack-tip stress shows a decreasing trend with the increase in the initial crack length. The stress at the crack-tip node is low in case of FGMs compared against the other two materials, viz. aluminium and Aluminium-Alumina composite materials. Thus almost all the parameters related to the fracture characteristics and the fracture toughness are low in case Aluminium-Alumina FGMs compared to the other two materials, viz. aluminium and Aluminium-Alumina composite materials.

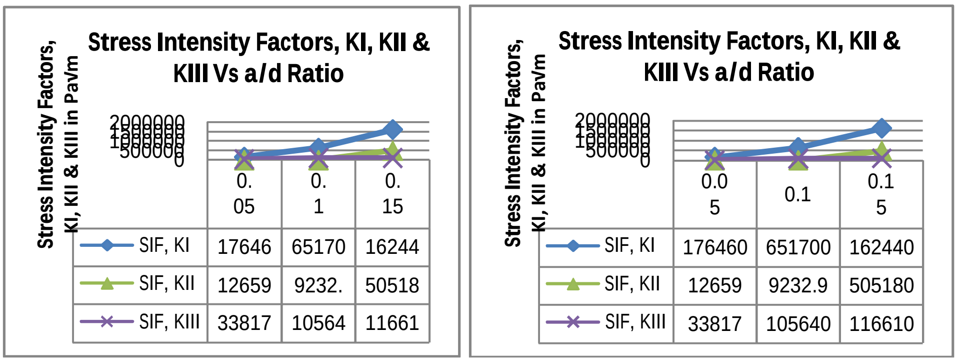

Fig. 2. Stress Intensity Factors, K_I, K_{II} & K_{III} Vs a/d Ratio for Aluminium and Aluminium-Alumina 15% Composite Model under the Uniform Load of 5000 N

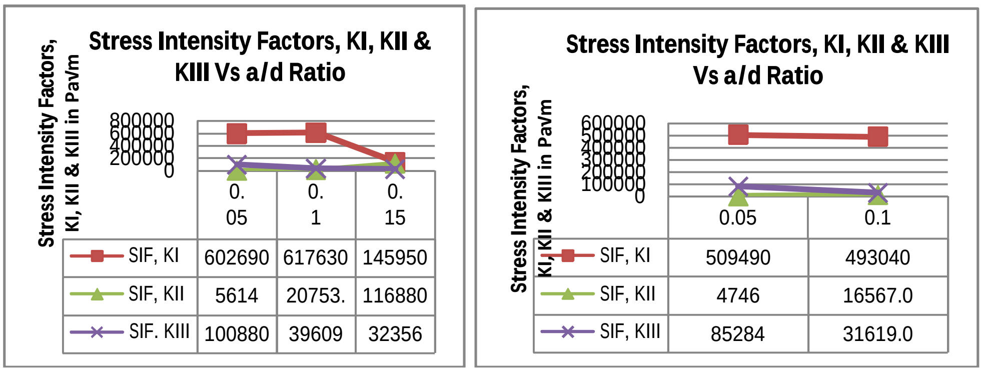

Fig. 3. Stress Intensity Factors, K_I, K_{II} & K_{III} Vs a/d Ratio for Aluminium-Alumina FGM model under the Load of 5000 N and under the Different Experimental Loads Carried by under Aluminium-Alumina 25% Composite Specimens

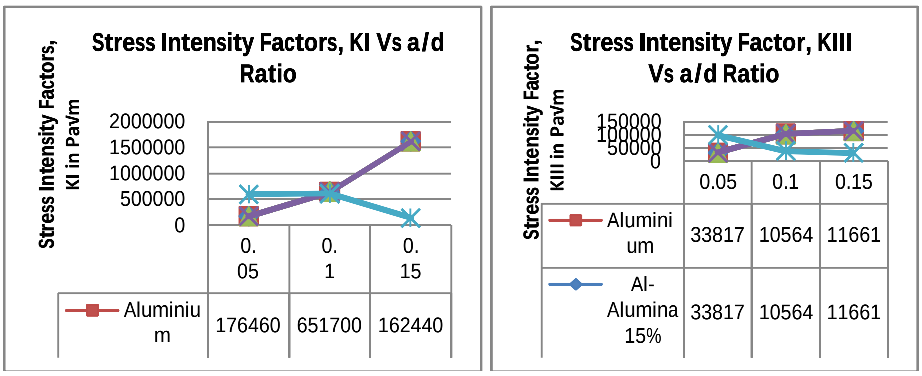

Fig. 4. Comparison of Stress Intensity Factors, K_I, and K_{III} Vs a/d Ratio between Different Material Models under the Load of 5000 N

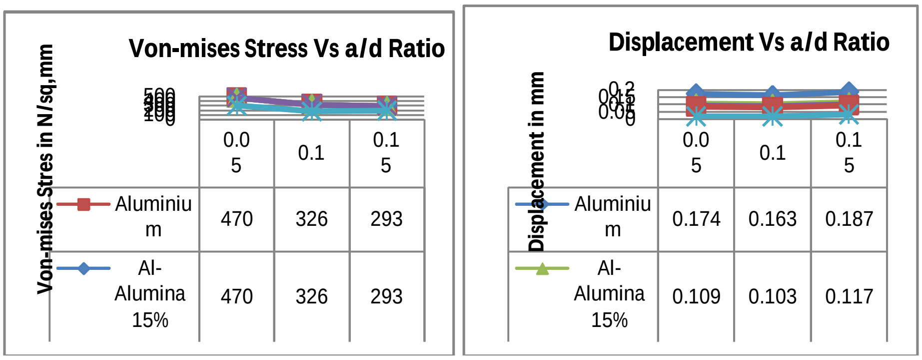

Fig. 5. Comparison of Von-mises Stress and Maximum Displacement Vs a/d Ratio Between Different Material Models under the Same Load of 5000 N

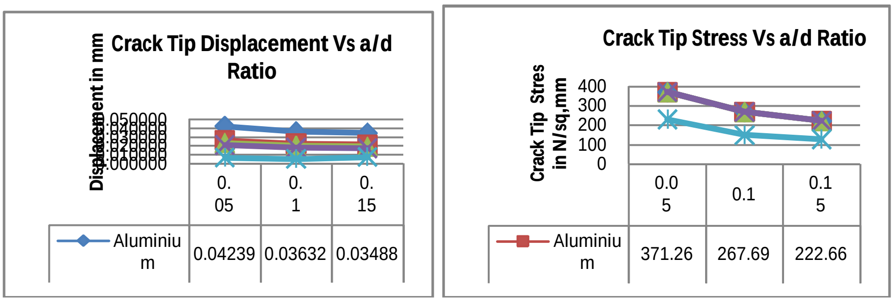

Fig. 6. Comparison of Displacement and Stress at Crack-tip Vs a/d Ratio between Different Material Models under Same Load of 5000 N

Conclusion

The fatigue characteristics of the aluminium and aluminium-alumina 15%, 20% and 25% composite specimens and aluminium-alumina FGM specimens have been obtained with specimens of different crack length through simulation techniques. In case of all the five materials, under flexural loading conditions, the predominance of Mode I Stress Intensity Factor, K_I over the other two modes has been clearly established. Under flexural loading conditions as established by the simulation of the experimental three point tests, opening mode prevails over the other two modes of fracture, viz. the sliding mode and the tearing mode.

The predominant Mode I Stress Intensity Factor, K_I keeps fairly low in case of aluminium-alumina FGMs compared to that of the specimens of isotropic aluminium and the different compositions of aluminium-alumina Composite materials. Thus, the suitability of the FGMs to replace the aluminium or aluminium composite materials for aerospace structural applications is proved. Also all three modes of Stress Intensity Factors are comparatively very low in case of FGMs.

The stress induced around the crack-tip region and the maximum deflections around the plate edge of the crack are comparatively very low in case of FGMs. The stress at the crack-tip node and also the crack-tip displacement have been observed to be low in case of FGMs compared against the other two materials, viz. aluminium and different compositions of aluminium-alumina composite materials.

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