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Microscale simulation of adhesive and cohesive failure in rough interfaces

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ABSTRACT

Multi-material lightweight designs, e.g. the combination of aluminum with fiberreinforced composites, are a key feature for the development of innovative and resourceefficient products. The connection properties of such bi-material interfaces are influenced by the geometric structure on different length scales. In this article a modeling strategy is presented to study the failure behavior of rough interfaces within a computational homogenization scheme. We study different local phenomena and their effects on the overall interface characteristics, e.g. the surface roughness and different local failure types as cohesive failure of the bulk material and adhesive failure of the local interface. Since there is a large separation in the length scales of the surface roughness, which is in the micrometer range, and conventional structural components, we employ a numerical homogenization approach to extract effective traction-separation laws to derive effective interface parameters. Adhesive interface failure is modeled by cohesive elements based on a tractionseparation law and cohesive failure of the bulk material is described by an elastic-plastic model with progressive damage evolution.

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1. Introduction

The application of fiber reinforced plastics (FRP) in multi-material lightweight structures requires innovative joining concepts to combine the advantages of FRP with conventional lightweight materials as aluminum. Such hybrids are e.g. essential to realize appropriate load transfer elements in automotive or aircraft applications [1,2]. Different from technologies like bolted or riveted joints, which generally induce damage in the composite material, approaches that create the connection during the forming process itself instead of a subsequent joining step are promising solutions. Despite the intrinsic joining process, component failure often initializes in the bonding zone as shown in Fig. 1, since the adhesive strength of polymermetal interfaces is often much lower than the cohesive strength of the connected materials [3,4]. The adhesion between two materials can be influenced by different mechanisms. These include chemical/physical-chemical mechanisms (hydrogen and van der Waals forces), electrostatic mechanisms (difference in electrical charge) and mechanical mechanisms (interlocking) [5]. This paper focuses on the latter mechanism by analyzing structured interfaces that create a mechanical interlock. For instance in Fig. 1, the design of a macroscopic waviness or an increased microscopic interface roughness due to a certain pre-treatment of the aluminum surface may improve the mechanical properties of the joint.

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Avertical expansion of idealized interface profilebwidth of microscale domainCautocorrelation functionD _{CDM} scalar damage variable of conteniuum damage modelD _{CCM} scalar damage variable of cohesive zone modelEYouxes's modulusfyield condition of plasticity modelG _c effective critical energy release rate in mode $l = 1, 11$ G _c effective critical energy release rate in mode $l = 1, 11$ hheight of microscale domainh/txistiffness of cohesive zone model in $l = n$ normal and $l = s$ shear directionLeffective critical energyLlength of measured height profile k_{i1} stiffness of cohesive zone model in $l = n$ normal and $l = s$ shear directionLength of measured height profile k_{i2} correlation length(·) ^M values related to the microscale(i) ^m values related to the microscale(i) ^m values related to the microscale(i) ^m values related vector on cohesive interfaceRarithmetic average of height profile k_{i2} cohesive traction vector on domain boundaryttraction vector on domain boundarytthe i-th discrete effective traction value μ_{i2}^{eff} equivalent plastic displacementugisplacement vector on value μ_{i2}^{eff} effective strange μ_{i1}^{eff} the i-th discrete effective traction value μ_{i2}^{eff} values related to plot on Γ_{e}^{A} x <	Nomenclature	
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$ \begin{aligned} $	G _c	effective critical energy
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\overline{u}^{pl} equivalent plastic displacement \overline{u} prescribed displacement vector on domain boundary $[[u]]_{c,i}^{M}$ the <i>i</i> -th discrete separation value $[[u]]$ separation vector on interface u displacement vector \overline{u}^{m} displacement fluctuation vector on microscale ∂W_{c}^{m} volume average of virtual work of microdomain ∂W_{c}^{M} virtual work at point on Γ_{c}^{M} x position vector δ_{m}^{m} mixed mode separation at damage initiation δ_{m}^{f} mixed mode separation at failure δ_{m} plastic part of strain tensor ε^{el} elastic part of strain tensor $\varepsilon^{pl.0}$ equivalent plastic strain at damage initiation $\overline{\rho}^{pl.0}$ equivalent plastic strain at failure $\overline{\rho}^{pl}$ plastic part of strain tensor $\overline{\rho}^{pl}$ equivalent plastic strain at failure $\overline{\rho}^{pl}$ equivalent plastic strain at failure $\overline{\rho}^{pl}$ equivalent plastic strain at failure $\overline{\rho}^{pl}$ position vector $\partial \Omega_{\overline{u}}$ Dirichlet boundary \mathcal{K} scalar multiplier in plastic evolution equation λ horizontal expansion of idealized interface profile γ Poisson's ratio Ω_{μ} domain of material phase + Ω_{-} domain of material phase - σ Cauchy stress tensor	$t_{\mathrm{c},i}^{\mathrm{M}}$	the <i>i</i> -th discrete effective traction value
uprescribed displacement vector on domain boundary $\llbracket u \rrbracket_{ci}^{l}$ the <i>i</i> -th discrete separation value $\llbracket u$ displacement vectorudisplacement fluctuation vector on microscale δW_c^{m} volume average of virtual work of microdomain δW_c^{k} virtual work at point on Γ_c^{M} \mathbf{x} position vector δ_m^{m} mixed mode separation at damage initiation δ_m^{f} mixed mode separation at failure δ_m mixed mode separation at failure δ_m mixed mode separation at failure δ_m glastic part of strain tensor e^{el} elastic part of strain tensor e^{pl} plastic part of strain at damage initiation ∂_{pl}^{l} equivalent plastic strain at failure e^{pl} equivalent plastic strain at failure ∂_{pl} equivalent plastic strain Γ cohesive interface γ horizontal expansion of modified triangular profile $\partial \Omega_{\overline{u}}$ Dirichlet boundary \mathcal{K} scalar multiplier in plastic evolution equation λ horizontal expansion of idealized interface profile γ Poisson's ratio Ω domain of material phase + Ω domain of material phase - σ Cauchy stress tensor	$\overline{u}^{\mathrm{pl}}$	equivalent plastic displacement
$ \begin{bmatrix} \mathbf{u} \\ \mathbf{u} \end{bmatrix} $ separation vector on interface $ \mathbf{u} $ displacement fluctuation vector on microscale $ \frac{\partial W_c^m}{\partial W_c^m} $ volume average of virtual work of microdomain $ \frac{\partial W_c^m}{\partial W_c^m} $ virtual work at point on Γ_c^m $ \mathbf{x} $ position vector $ \frac{\partial}{\partial m} $ mixed mode separation at damage initiation $ \frac{\partial}{\partial m} $ mixed mode separation at failure $ \frac{\partial}{\partial m} $ plastic part of strain tensor $ \frac{\partial}{\partial P^{10}} $ equivalent plastic strain at damage initiation $ \frac{\partial}{\partial P^{10}} $ equivalent plastic strain at failure $ \frac{\partial}{\partial P^{10}} $ equivalent plastic strain at failure $ \frac{\partial}{\partial P^{10}} $ equivalent plastic strain at failure $ \frac{\partial}{\partial P^{10}} $ Neumann boundary $ \frac{\partial \Omega_{\overline{u}} $ Dirichlet boundary $ \frac{\partial}{\partial \Omega_{\overline{u}} $ domain of material phase + $ \frac{\partial}{\partial \Omega_{\overline{u}} $ domain of material phase - $ \mathbf{\sigma} $ Cauchy stress tensor	u M	the i th discrete constration value
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$\hat{\mathbf{u}}^{m}$ displacement fluctuation vector on microscale δW_{c}^{m} volume average of virtual work of microdomain δw_{c}^{M} virtual work at point on Γ_{c}^{M} \mathbf{x} position vector δ_{m}^{0} mixed mode separation at damage initiation δ_{m}^{f} mixed mode separation at failure δ_{m} mixed mode separation \mathbf{z} strain tensor \mathbf{z}^{el} elastic part of strain tensor \mathbf{z}^{pl} plastic part of strain tensor \mathbf{z}^{pl} equivalent plastic strain at damage initiation \mathbf{z}^{pl} equivalent plastic strain at failure \mathbf{z}^{pl} equivalent plastic strain at failure \mathbf{z}^{pl} equivalent plastic strain $\mathbf{\Gamma}$ cohesive interface γ horizontal expansion of modified triangular profile $\partial \Omega_{\overline{\mathbf{t}}}$ Neumann boundary $\partial \Omega_{\overline{\mathbf{t}}}$ Dirichlet boundary \mathcal{K} scalar multiplier in plastic evolution equation λ horizontal expansion of idealized interface profile v Poisson's ratio Ω domain Ω_{+} domain of material phase + Ω_{-} domain of material phase - $\mathbf{\sigma}$ Cauchy stress tensor	u	displacement vector
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$\begin{array}{llllllllllllllllllllllllllllllllllll$	г Г	cohesive interface
$\begin{array}{llllllllllllllllllllllllllllllllllll$	v	horizontal expansion of modified triangular profile
$\begin{array}{lll} \partial \Omega_{\overline{u}} & \mbox{Dirichlet boundary} \\ \kappa & \mbox{scalar multiplier in plastic evolution equation} \\ \lambda & \mbox{horizontal expansion of idealized interface profile} \\ \nu & \mbox{Poisson's ratio} \\ \Omega & \mbox{domain} \\ \Omega_+ & \mbox{domain of material phase +} \\ \Omega & \mbox{domain of material phase} & - \\ \sigma & \mbox{Cauchy stress tensor} \end{array}$	$\partial \Omega_{\overline{t}}$	Neumann boundary
κ scalar multiplier in plastic evolution equation λ horizontal expansion of idealized interface profile ν POISSON'S ratio Ω domain Ω_+ domain of material phase + Ω domain of material phase - σ Cauchy stress tensor	$\partial \Omega_{\overline{u}}$	Dirichlet boundary
λ norizontal expansion of idealized interface profile ν Poisson's ratio Ω domain Ω_+ domain of material phase + Ω domain of material phase - σ Cauchy stress tensor	κ	scalar multiplier in plastic evolution equation
$ \begin{array}{l} \Omega \\ \Omega \\ \Omega_{+} \\ \Omega_{-} \\ \sigma \end{array} \begin{array}{l} \text{domain of material phase +} \\ \Omega_{-} \\ \text{domain of material phase -} \\ \sigma \\ \end{array} $	λ V	norizoniai expansion oi idealized interface profile
$\begin{array}{llllllllllllllllllllllllllllllllllll$	Ω	domain
$\begin{array}{llllllllllllllllllllllllllllllllllll$	Ω_+	domain of material phase +
σ Cauchy stress tensor	Ω_{-}	domain of material phase –
	σ	Cauchy stress tensor

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