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Fracture analysis of a metal to CFRP hybrid with thermoplastic interlayers for interfacial stress relaxation using in situ thermography

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ABSTRACT

In this work a plane hybrid-structure composed of a metal and a carbon-fiber-reinforced-polymer (CFRP) constituent is introduced. Hereby an interlayer is inserted between the metal and the CFRP constituent, pursuing the task of stress relaxation. In order to study the effect of interfacial stress relaxation several thermoplastics are investigated. In situ passive thermography is used to assess the damage during quasi-static and fatigue mechanical loading. Thus, mechanical properties are correlated with corresponding damage-quantities from non-destructive testing (ndt). These results reveal that transversal cracking and mode-I delamination are the dominant failure processes, which strongly depend on the thermoplastic material. Additional finite element analysis describes strain-energy- and stressconcentrations, which coincide with the observed damage mechanisms and the origins of fracture.

1. Introduction

With an increasing application of multi-material hybrids, i.e. metal to carbon-fiber-reinforced polymer (CFRP) hybrids, the subjects of fatigue and corrosion resistance at the inherent interfaces become more and more important. Contemplating the fatigue related damage behavior of such hybrid-joints, the fundamental understanding of the underlying fields, i.e. CFRP related damage mechanisms, mechanics, joining and interfaces as well as non-destructive testing techniques, is the key factor.

In order to evaluate the life-cycle performance of CFRPs, different criteria have been developed, i.e. energy-, damage-tensor based and fracture mechanical models [1]. The damage-tensor approach is mostly applied, when major attention is paid to the macroscopic behavior [2,3]. A more differentiated view is given by [4,5], summarizing the various failure mechanisms in composite materials with corresponding estimations of the failure-energy. Specific fracture energies are also cited for transverse fiber fracture, 20–60 kJ/m^2, and delamination, 100–3000 J/m^2 depending on matrix material and strain rate, respectively. Ultimately, the evaluation of the life-cycle performance can be enhanced by integrating non-destructive testing [5–7].

Meanwhile, thermography has been applied for quantitative damage characterization under quasi-static [8] and fatigue loading [9–11]. Thereby, based on the constitutive relation between stresses, strains and temperature, thermography signal mapping was enabled. In particular, CFRP inherent poor heat conductivity and low density are beneficial for improved signal to noise ratio. The poor heat conductivity is also advantageous for the thermo-elastic stress analysis (TSA). In case of CFRP, the required adiabatic conditions are met at sufficiently high loading frequencies, such that a linear relation between temperature and the first stress invariant is obtained. Hence, the thermographic signal can be used to determine the distribution of principal stresses in an orthotropic material [12,13]. Care has to be taken, as numerical preprocessing might be necessary due to CFRP-inherent noisy raw data and unreliable thermographic data at boundary edges, which estimates stresses too low [12,13]. However, the stress-separation process, proposed by Lin and Feng [12,13] does not apply for shear stresses and out-of plane stresses, e.g. mode-I loading, which is a drawback of the technique.

Palumbo et al. [14] discuss the thermography signal, composed of the mean temperature and the reversible temperature variations that are modulated by externally applied stress waveforms. The latter incorporates the amplitude and phase information, given in the thermo-elastic signal. If heat exchange is absent and considering that the global temperature increase is zero within a cycle, it is possible to evaluate the surface stresses by monitoring the modulated surface temperature from

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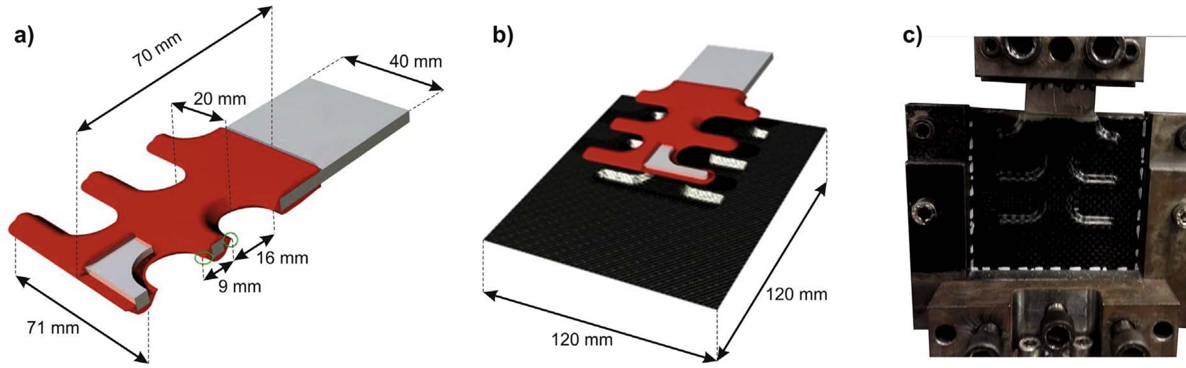

Fig. 3.1. a) geometry of the Al-Thermoplastic insert b) position of the insert in the CFRP-laminate c) fixation of the specimen, dashed lines illustrate the area captured with thermography.

a body. Further, Palumbo et al. [14] report that no reference image is needed, when evaluating the obtained phase-information. Further, the signal to noise ratio of the damage mapping is vastly improved. They point out that heat build-up measurements lead to an overestimation and the phase of thermo-elastic data lead to an underestimation of the fatigue limit, compared to the obtained S-N curves. Further investigations on CFRP-components demonstrate the capabilities of thermography to identify the location of failure [8,14–17]. Thereby thermography data agrees well with acoustic emission [11], digital image correlation [17] and ultra-sonic analysis [18]. Using the local heat conduction equation [19], various studies predicted the upcoming failure of specimens based on heat build-up measurements [9,20,21] and dissipative thermal energy [11], respectively. In the latter study, SEM-images reveal three fatigue states, in which matrix micro-cracks, crack-growth towards the fiber-matrix interface and subsequent delamination and fiber breakage are the dominant mechanisms. Additionally, ply delamination was often observed to go along with macroscopic failure [17].

However, when dealing with metal-CFRP hybrids, bonding and mechanical gradients at the interface play a major role for the mechanical properties of the joint [22]. In most of recent investigations on that subject [23], the joining is achieved by adhesives, screws or pins, resulting in a mechanical gradient at the interface. Moreover, several works report a crack promoting effect due to the mechanical gradient and due to interpenetration of the constituents [24–26]. The integrity of the laminate may further be disturbed by imperfections, e.g. delaminations or fiber ondulations [27,28]. Pohl et al. [29] developed a new hybrid-structure, inserting a thermoplastic layer between the aluminum and the CFRP constituent for interfacial stress relaxation. Investigations on that approach have yet focused on evaluating quality critical attributes [30,31]. Hence, a lack of knowledge exists on the subject how the material properties at the intrinsic interfaces affect the fatigue related damage evolution.

Therefore, a comparative study is presented in this work, focusing on the damage development and mechanical performance of the hybrid, as influenced by the thermoplastic interlayer. Three different thermoplastic materials as well as a reference without the thermoplastic layer are investigated under quasi-static and fatigue loading. To validate the damage related link between experimentally determined thermographic quantities and effective stresses, additional finite-element modelling (FEM) is carried out, showing the stress distribution for the different materials.

2. Theoretical framework

Both, effective stresses and the materials response, i.e. deformation, result in the intrinsic dissipation. Chrysochoos and Louche [19] give a general formulation for the intrinsic dissipation by means of the time dependent temperature change $\dot{T}$:

$$\rho C_{\varepsilon,\underline{\alpha}}\frac{dT}{dt} + div\,\underline{q} = d_1 + \rho T\psi_{,T,\varepsilon}:\frac{d\varepsilon}{dt} + \rho T\psi_{,T,\underline{\alpha}}\cdot\frac{d\underline{\alpha}}{dt} + r_e \tag{1}$$

where ρ denotes the density, $C_{\underline{\varepsilon},\underline{\alpha}}$ the specific heat capacity at constant ε and $\underline{\alpha}$, $\underline{q}$ the heat flux vector, ψ the specific Helmholtz free energy and r_e the external heat supply. Further, the set of n + 1 thermodynamic state variables are denoted by temperature T, strain $_\varepsilon$ and the symbolic vector $\underline{\alpha}$ of n-1 internal variables α_j. Note that the intrinsic dissipation d_1 can be described as the sum of anelastic W_a’ and stored W_s’ energy rate.

$$d_1 = W_a' - W_s' = \underline{\sigma}: \underline{D} - \rho\psi_{,\varepsilon}: \frac{d\varepsilon}{dt} - \rho\psi_{,\underline{\alpha}}\cdot\frac{d\underline{\alpha}}{dt} \tag{2}$$

Jegou et al. [21] simplified Eq. (1), since variations of ρ and $C_{\varepsilon,}\underline{\alpha}$ as well as couplings between internal variables other than ε can be neglected for temperature variations below 10 K. Moreover, the second term on the right hand side of (1) can be identified as the thermoelastic temperature change. The heat loss q can be calculated using the general equations for convection and conduction [32]. However, the derived equation relates any temporal change in temperature to a change in the materials internal state. In other words, any measureable local temperature change indicates superposed thermoelastic and dissipative mechanical work, i.e. cracking.

3. Specimen assembly

The hybrid-structure under investigation consists of a metallic plate that is inserted between the center plies of the CFRP-laminate. A geometrical optimized thermoplastic layer is placed between those constituents resulting in a tight fit [29]. A further goal is the reduction of the contact pressure and stress concentrations at the interfaces.

The specimens are produced by direct injection-overmolding of a 4 mm thick metallic insert, Aluminum EN AW 6082 (AlMgSi1), with a 2 mm thick thermoplastic polymer. The Al-polymer compound is inserted between the center plies of the CFRP-laminate (see Fig. 3.1) within the resin transfer molding (RTM) process. Hence, all four plies are consolidated together. The consolidation is carried out at a temperature of 348 K and a pressure of 800 kPa. The pore content is not measured. The CFRP consists of four laminate plies $[0/90°, \pm 45°]_s$ with 30 vol-% 3 K plain weave (Torayca FT300B) carbon fiber embedded in an epoxy matrix (Biresin CR170/CH150-3). Each ply has a thickness of 0.25 mm. The chosen layup results in quasi-isotropic mechanical properties in the main directions.

In this work a reference configuration and three different thermoplastics are investigated. As interlayer material, a soft and highly elastic Polyurethane (TPU, covestro Desmopan® 487, E-modulus: 36 MPa), a high rigid Polyphthalamid reinforced with 30 vol-% short glass-fibers (PPAGF30, Vestamid® HT plus M1033, E-modulus: 11.2 GPa) and the same Polyphthalamid without reinforcement (PPA, Vestamid® HT plus M1000, E-modulus: 3.5 GPa) are chosen. The Al insert used for the reference configuration has a similar contour as the Al-polymer insert and is hereafter denominated as full-Al insert.