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Improvement of fatigue life by compliant and soft interlayers

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ABSTRACT

Retardation of fatigue crack growth rate due to the introduction of thin, compliant and/or soft interlayers is investigated. The mechanism is the reduction of the crack driving force in the interlayer. Fatigue tests are conducted on composites made of high-strength aluminum alloy as matrix and technically pure aluminum or adhesive as interlayer material. The adhesive interlayer causes an increase in fatigue life by a factor 20 or more, whereas the aluminum interlayer yields only a moderate improvement. Numerical simulations based on the configurational force concept are utilized for understanding. The results show new possibilities for the design of fatigue-resistant materials.

Spatial variations in material properties have a large influence on the crack driving force, i.e. a material inhomogeneity can accelerate or decelerate crack propagation. This effect has been known already for a long time, e.g. see the literature reviews given in [1,2]. However, a reliable method to quantify the effect has been found only recently by application of the concept of configurational forces, e.g. [3,4]. This concept has allowed us to predict the behavior of cracks in various types of inhomogeneous materials and composites [1,5–8]. The material inhomogeneity effect can be utilized for the design of future fracture resistant materials [9–12]. Especially interesting in this respect is the introduction of thin, compliant and/or soft interlayers in high-strength matrix materials with low intrinsic toughness. Numerical investigations have shown that these interlayers work as effective crack arresters, which may lead to a tremendous increase of fracture toughness at almost negligible loss in stiffness [11,12]. Experimental studies have confirmed the theoretical findings [13,14]. Purpose of the current study is to investigate whether such compliant and/or soft interlayers do have also a beneficial effect on the fatigue resistance of materials.

A material inhomogeneity provides a crack-tip shielding effect, i.e. it leads to a decrease of the crack driving force, if the crack propagates from a material with a lower Young's modulus or lower yield stress towards a material with a higher Young's modulus or yield stress (compliant/stiff or soft/hard transitions) [1,5,8,9]. In the cases of stiff/compliant or hard/soft transitions, crack growth is promoted, since the material inhomogeneity has an anti-shielding effect. It should be noted that the material inhomogeneity effect does not require interface decohesion, i.e., it appears also with perfect interfaces. The effect even occurs, if no interface is present and Young's modulus or yield stress exhibit smooth variations as, e.g., in functionally gradient materials [1,9]. Therefore, the material inhomogeneity effect is fundamentally different from the well-known effects of interface opening and crack deflection that are not treated in this paper.

If compliant or soft interlayers are introduced in a stiff, high-strength matrix material, we have anti-shielding at the 1st and shielding at the 2nd interface of the interlayer [2,9,11,12]. The situation at the 2nd interface is critical for the fracture toughness of the composite, since the crack will arrest, if the crack driving force becomes small enough. It has been found that the multilayer must fulfill certain architectural requirements for providing crack arrest: The material property variation must be large enough and the distance between the interlayers must be small enough, depending on the applied stress [2,11,12,15]. It should be also noted that a material inhomogeneity can influence the crack path [8]. The concept of configurational forces enables us to predict the crack growth direction. An example, crack deflection of a fatigue crack near an inclined bimaterial interface, has been presented in [8].

In principle, it should be possible to transfer the idea of providing crack arrest by a material inhomogeneity to fatigue crack propagation. In [16] the configurational force concept has been applied to predict the variation of the crack growth rate in bi-material specimens. The predictions are in good qualitative and quantitative agreement with the experiments of [17,18]. A significant increase of the fatigue life by the introduction of a soft Ni-5Al interlayer between steel and a Cr_2O_3-coating was found experimentally already in [19]; more recent

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examples can be found in literature, e.g. [20]. Purpose of the current study is, therefore, to investigate experimentally and numerically fatigue crack growth in layered composites, which either have an inhomogeneity in Young's modulus and/or yield stress.

Fatigue tests are carried out on multilayers based on 3.18 mm thick sheets of high strength aluminum alloy Al7075-T6 as matrix material. In the first multilayer type, the Al7075 sheets are combined by a two-component methacrylate adhesive, WELD-ON® SS315. This type is denominated in the following as "Al/glue-multilayer". In the second type, denominated as "Al/Al-multilayer", the interlayers consist of technically pure aluminum, Al1050; the composite is joined by roll bonding. The Young's modulus E, the yield strength σ_y and the ultimate tensile strength σ_u of the constituents are given in Table 1. The mechanical properties of Al7075 and Al1050 are determined in tensile tests; the data of the adhesive are provided by the producer. Young's modulus and strength of Al7075 and the adhesive vary by factors of approximately 300 and 40, respectively, exhibiting a strong $(E+\sigma_y)$ - inhomogeneity at the interfaces of the Al/glue-multilayers. The Al/Al-multilayers exhibit only a σ_y - inhomogeneity, but the yield stress varies by a factor of 5 at the interfaces, which fulfills the criterion found in [2]. Fracture mechanics tests conducted on single-edge notch tension (SENT) specimens gave tremendous improvements of the J-integral values measured at maximum load: $J_{F_{\max}}=900\,\mathrm{kJ/m^2}$ for the Al/Al-multilayer [21] and $J_{F_{\max}}=10500\,\mathrm{kJ/m^2}$ for the Al/glue-multilayer [13], compared to a value of 30 kJ/m^2 for homogeneous Al7075.[2]

The Al/glue-multilayer specimens are manufactured by degreasing the laser-cut Al7075 sheets with ethanol and connecting them with 0.1 mm thick adhesive layers. Before further machining, the specimens are cured 24 h at room temperature so that the adhesive reaches its maximum strength. A preliminary fatigue experiment is conducted on a double-edge notch tension specimen consisting of 5 Al- and 4 adhesive layers, Fig. 1a. The specimen dimensions are indicated in the figure; the notch depth is 1.2 mm. The specimen is cycled at constant load amplitude $\Delta F=27$ kN and load ratio $R=F_{\min}/F_{\max}=0.1$ at a frequency of 15 Hz. The fatigue cracks need approximately 42.000 cycles to grow through the pre-notched outer layers. Subsequently, the cracks arrest in the interlayers without any delamination. It needs additional $1.8\cdot10^6$ cycles to re-initiate a crack in a previously undamaged layer. Due to the increasing stress intensity, the crack grows quickly through this layer and the remaining specimen ligament. Fatigue failure of a homogeneous specimen of the same geometry, loading and initial notch length would occur after 10^5 cycles. Thus, the adhesive interlayers increase the fatigue life by a factor of approximately 19.

Two further experiments are performed on SENT specimens under constant applied stress intensity range ΔK_{appl}. Specimen 1 has the same outer dimension and layer geometry as the preliminary specimen (Fig. 1a). The machined notch is sharpened with a razorblade and diamond paste; the initial crack tip lies in the middle of the central Al-7075-layer. Specimen 2 has a different geometry (Fig. 1b) and consists only of two Al7075 sheets and a single 0.05 mm thick adhesive layer. A 1 mm razorblade sharpened notch is machined into the specimen. The reason for performing one test on a multilayer and another on a specimen with a single interlayer is that the spacing between the soft interlayers could have an influence on the material inhomogeneity effect, see [9,11,12,15]. This is easily understood for the case of a σ_y - inhomogeneity: The material inhomogeneity effect is highest, if the radius of the crack tip plastic zone of the interlayer material, $r_{\mathrm{pl}}^{\mathrm{IL}}=(1/6\pi)(K_{\max}/\sigma_y^{\mathrm{IL}})^2$, has approximately the magnitude of the interlayer thickness [2,9]. If the interlayer spacing is much larger than $r_{\mathrm{pl}}^{\mathrm{IL}}$, the material inhomogeneity effect in the multilayer equals that in a single interlayer. However, the effect diminishes, if the interlayer spacing is smaller than $r_{\mathrm{pl}}^{\mathrm{IL}}$. If the interlayer spacing is so low (or the load is so high) that the plastic zone covers many interlayers, the shielding and anti-shielding effects of the various interfaces in the multilayer compensate and the material inhomogeneity effect becomes zero. In contrast to the σ_y-inhomogeneity effect, the effect of E-inhomogeneity is not confined to the crack tip plastic zone and, in general, more far-reaching. For this case and for the $(E+\sigma_y)$ - inhomogeneity, the optimum multilayer configurations have not been worked out so far.

Table 1
Mechanical properties of the constituents of the multilayers.

	E [GPa]	σ_y [MPa]	σ_u [MPa]
Al7075-T6	70	520	580
Adhesive	0.24	11	15
Al1050	70	105	115

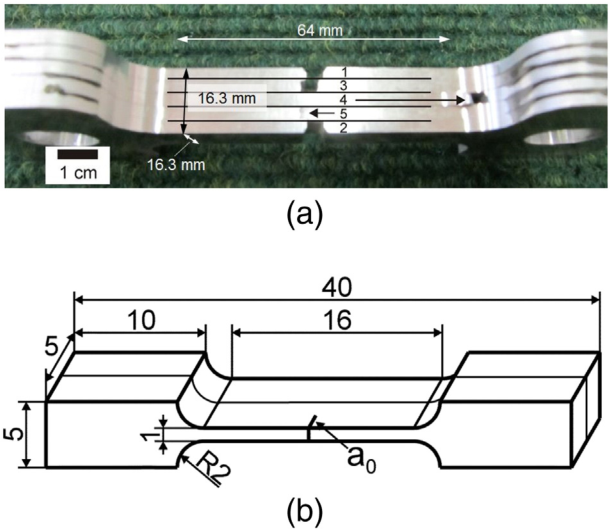

Fig. 1. (a) Preliminary double-edge notched Al/glue-multilayer specimen; the numbers indicate the sequence in which the individual layers fail. (b) Al/glue-Specimen 2 consisting of two Al7075 sheets and a single adhesive layer.

Fatigue tests are conducted with $\Delta K_{\mathrm{appl}}=K_{\max}-K_{\min}=9\ \mathrm{MPa}\sqrt{\mathrm{m}}$ and $R=0.1$. The tests are periodically stopped after intervals, consisting of 250 to 1000 cycles, in order to measure the crack extension Δa on both sides of the specimen and adapting the load. For every interval, the average crack growth rate is calculated.

In Fig. 2, the crack growth rates da/dN are plotted against the distance d between crack tip and (the first interface of) the interlayer. The interface positions are marked by vertical black lines. For comparison, the crack growth rate calculated from the Paris-relation given in [22] for homogeneous Al7075-T6, $(da/dN)_{\mathrm{hom}}\cong1\cdot10^{-4}$ mm/cycle, is drawn as horizontal dashed line. This value is observed for large distances, $d<-1.5$ mm. For shorter distances, da/dN increases and reaches close to the interface a maximum value that is ~15 times higher. The fatigue crack grows into the compliant interlayer but arrests there. Crack growth through the first Al7075 and adhesive layers needs 9500 and 3250 cycles for Specimens 1 and 2, respectively. Additional $4.6\cdot10^6$ cycles are applied to Specimen 1 without any crack growth. According to the Paris-relation [22], final fracture of a homogeneous Al7075 specimen would occur after 10^5 cycles. Thus, the adhesive

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[2] Multilayer configuration and outer geometry of the fracture mechanics specimens were similar to that of the multilayer fatigue specimens, see below, but they had only a single notch. The initial crack tip was located in the central Al7075 layer. Crack growth started at $J_c=25\div30$ kJ/m^2, but the crack then arrested in the interlayer. After crack arrest, the specimens behaved like tensile specimens and fractured at the plastic limit load of the remaining ligament. This is the reason for the very high $J_{F_{\max}}$-values; see [13] for the determination of these values. It should be noted that the J-integral at maximum load, $J_{F_{\max}}$, depends on the specimen geometry; this is typical for a parameter describing an instability process. The main reason why the Al/Al composite shows a lower $J_{F_{\max}}$ than the Al/glue composite is that the Al-interlayer seems to trigger local necking of the Al7075, which leads to a lower maximum load $F_{\max}$, whereas necking starts at a much later stage in the Al/glue composite.