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Design of Damage-tolerant and Fracture-resistant Materials by Utilizing the Material Inhomogeneity Effect

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Deep-sea glass sponges have a microstructure consisting of layers made of a brittle bulk material (bio-glass) with high elastic modulus connected by thin, compliant interlayers (protein). Numerical modeling and application of the concept of configurational forces has revealed that the multi-layered structure with strong spatial variation of the Young's modulus is responsible for the especially high fracture toughness of the glass sponge [1]. The reason is that the crack driving force is strongly reduced if the crack tip enters the soft protein interlayer.

This idea has been extended also to non-elastic materials [2], since the beneficial effects of material property variations also occur, if the Young's modulus is constant, but the yield stress exhibits a strong spatial variation. Figure 1 shows the decrease of the crack driving force, measured in terms of the near-tip J-integral J_{tip}, due to a single soft interlayer (IL). The critical position for possible crack arrest is located at the second interface of the IL, but on the side of the matrix material (M).

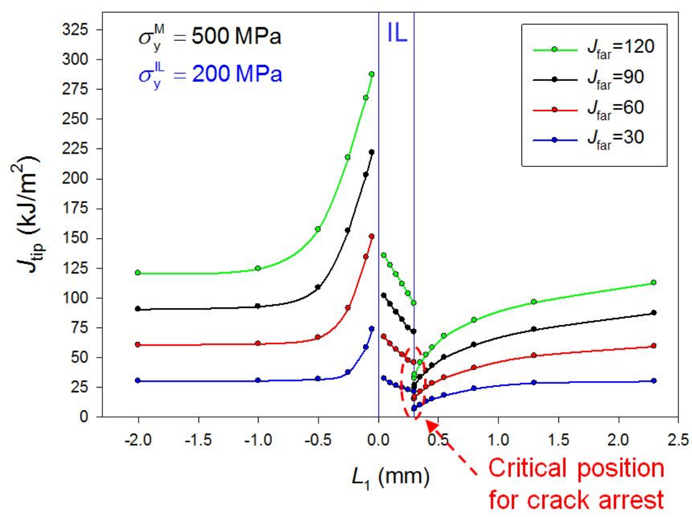

Fig. 1: Variation of crack driving force J_{tip} for crack tip positions near a single soft interlayer

In order to increase fracture stress and fracture toughness of multilayered composites made of inherently brittle bulk materials, the composite architecture has to fulfill certain design rules. Decisive influence factors for a multilayer configuration made of a given matrix material are the yield strength of the IL, the IL-thickness and the IL-spacing. Optimum interlayer configurations have been deduced by combining finite element analyses with the configurational forces concept and analytical estimates [2].

Various experiments have been conducted to check the theoretical findings, see e.g. [3]. Single-IL and multilayer compounds consisting of high-strength steels as matrix and a low-strength steel as interlayer material were manufactured by hot-forging. Fracture mechanics experiments exhibit a strongly increased fracture toughness compared to the homogeneous matrix material. An example is presented in Fig. 2. The matrix consists of a cold working steel C45 with a yield strength of 1660 MPa, the IL-material is an interstial-free steel DC04 with a yield strength of 390 MPa. The specimen with a single IL of 100 µm thickness shows a low fracture initiation toughness of $J_\mathrm{i} = 10\ \mathrm{kJ/m^2}$, and the crack rapidly grows to the IL and arrests there. (The homogeneous matrix material exhibits catastrohically brittle fracture at this load.) During further loading, the specimen behaves like a specimen without crack. The specimen fails after reaching the plastic limit load of the matrix material, at $J_\mathrm{max} \approx 3350\ \mathrm{kJ/m^2}$.

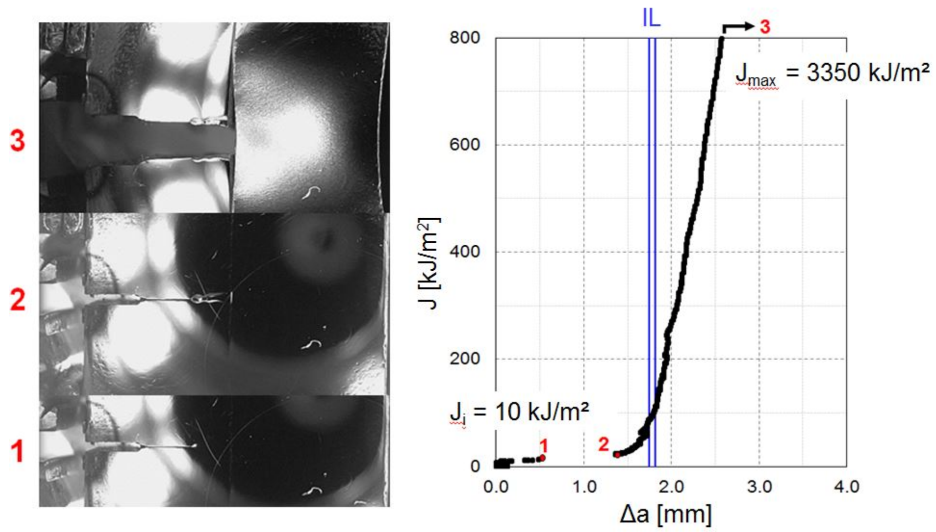

Fig. 2: Fracture mechanics experiment on a single-IL steel specimen. On the left, the specimen is depicted shortly after initiation of crack growth (1), at crack arrest (2), shortly before final fracture (3)

Acknowledgments

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