MATRIX DAMAGE HEALING IN FIBER REINFORCED COMPOSITE MATERIALS CONTAINING EMBEDDED WIRES

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ABSTRACT

Continuous fiber reinforced composite materials are susceptible to delamination damage. Healing of the damage in composite materials with a thermoplastic matrix is possible by a thermal approach. Heating the damaged material for a sufficiently long time allows healing/welding of the softened matrix material by a reptation process. Polymer molecules from one side of the delamination diffuse to the other side and vice versa, giving strength to the healing interface. This process is strongly temperature and time dependent. A necessary requirement is that both sides of the damaged region touch under a mild compressive stress. Pre-strained shape memory wires oriented in the out-of-plane direction are one way of imposing this stress at elevated temperature during the healing stage. While heating up the material the wires contract and compress the delaminated regions. Recent theoretical work in this field by the current authors confirms this idea [1]. Moreover it shows that also shape memory wires that are not pre-strained and plain glass, carbon and metal wires would in principle be able to raise a sufficiently high compressive stress at the healing temperature. In the latter case the thermal expansion of the thermoplastic matrix material, which is much larger than that of the wire material used in the out-of-plane direction, is the main cause of the pressure buildup.

In this work the generated ideas are experimentally verified for a model case where the wires are employed to support the consolidation process of pre-impregnated layers of composite material. The consolidation process can be seen as an extreme case of "damage" healing as all layers are separate at the start of the process, representing a multi-delaminated composite material. The quality of the healing process is determined by means of a mode I fracture toughness test using Double Cantilever Beam (DCB) specimens. Samples were prepared in the following way. Two stacks of 10 layers of 2 cm × 20 cm Uni-Directional (UD) Carbon Fibre (CF) reinforced PolyEther Imide (PEI) resin pre-pregs (fiber volume fraction is 62 %) are placed on top of each other with a 13 μm thin 2 cm x 6.5 cm polyimide Kapton® film placed between the stacks on one side to initiate a crack during the DCB tests. Two steel moulds of the same width as the specimens are placed on both sides of this stack. Metal plates are placed on the sides of the stack in order to prevent excessive matrix flow. Subsequently, a lathe was used to continuously wind wires accurately spaced around the mould. In this way the effect of the presence of out-of-plane wires can be studied relatively easily, without actually manufacturing complicated composite materials with woven-in wires. Three types of wires were used at appropriate wire fractions: (i) a Nitinol shape memory wire (not pre-strained), (ii) a carbon fiber bundle and (iii) a glass fiber bundle. Relevant mechanical properties of all materials used are given in Table 1. The healing / consolidation stage consists of heating up the samples in a pre-heated oven at 325 °C for 13 minutes and slow cooling to room temperature in approximately 30 minutes. The same type of CF/PEI samples was also prepared with a 25 cm × 25 cm closed mould hot-press under similar conditions for reference purposes. In this case a constant pressure of 7.2 bars was applied during the manufacturing process. After pressing, samples with the same dimensions as mentioned above were cut from the plate along the fiber direction. Subsequently, end tabs were glued to all samples and DCB tests were performed with an in-house developed automated DCB setup mounted in a standard tensile tester employing a displacement rate of 3 mm/min. The recorded force and displacement data are used to determine the critical energy release rates G_{Ic} of all samples applying the appropriate ISO/ASTM procedures and correction methods.

Table 1: Mechanical properties of wire materials.

Material	E [GPa]	α 10^{-6}/K	f_{wire} %
SMA (*martensite*)	30	6.7	0.04
SMA (*austenite*)	70	10.5	0.04
Carbon	230	-0.7	0.4
Glass	70	4.8	1.6

The results of the DCB testing of the samples manufactured with the use of out-of-plane wires wound around the mould (numbers 1 to 6) and the reference sample manufactured with a standard hot-press (number 0) are shown in Table 2.

Table 2: Results of double cantilever beam tests.

Number	Wire material	G_{Ic} [kJ/m^2]	
0	Reference	1.25	
1 & 2	SMA	1.1	1.5
3 & 4	Carbon	0.4	0.55
5 & 6	Glass	-	0.55

It can be seen clearly that the critical energy release rates of the samples manufactured with support of 0.04 % of SMA wires (samples 1 and 2) are of the same order of magnitude as that of the reference sample (sample 0). This means that the healing / consolidation process for both types of samples has progressed to the same level. It proves that SMA wires are indeed capable of supplying sufficient compressive stress as to completely heal / consolidate a stack of UD plies. The use of carbon and glass fibers wound around the moulds is less successful. The critical energy release rates of these samples are at least a factor of two smaller. In case of the glass fibers one sample even failed prematurely. This indicates that the healing / consolidation process has not progressed as far in these samples as in the case with the SMA wires and the reference sample. This seems strange at first sight, since all samples have undergone the same heat treatment, i.e. they experienced the same temperature profile as a function of time. However, an essential part of the consolidation process is local plastic flow at elevated temperatures to establish intimate contact at the interface of successive plies. Only when such contact is present, polymer interdiffusion (reptation) can take place locally providing strength to the interface. Differences occurring in the interface strength, as reflected by the different values of the critical energy release rates can then be explained by differences in the pressure (compressive stress) path over the course of the healing / consolidation heat treatment for the respective wires employed. We expect that the main differences will occur during the cooling stage of the heat treatment where due to the pseudo-elastic behavior of the SMA wires a compressive stress will be maintained over a long temperature decrease, whereas for the other wires the compressive stresses decay much more rapidly (on an absolute scale) also taking some degree of plastic deformation at elevated temperatures into account. This is subject to further study.

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[1] T.C. Bor, L. Warnet, R. Akkerman and A. de Boer, Modeling of Stress Development During Thermal Damage Healing in Fiber-reinforced Composite Materials Containing Embedded Shape Memory Alloy Wires L. Sorensen, *Journal of Composite Materials*, **44**,2010, pp. 2547 – 2572.