DAMAGE MECHANISMS OF NANOPARTICLE-MODIFIED CFRP UNDER VERY HIGH CYCLE FATIGUE-LOADING

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Abstract

In this work the influence of different types of carbon nanoparticles like multi-walled carbon nanotubes and few layered graphene on the damage mechanisms of CFRP under HCF and VHCF-fatigue loading are investigated. An improvement of fatigue life and change in dominating damage mechanism due to the nanoparticle modification were revealed.

1. Introduction

Due to their high specific static and fatigue strength carbon fibre reinforced polymers (CFRP) are often used for applications in lightweight structures under cyclic loadings in aircraft and wind industry, automotive engineering as well as general machine building. For achieving a maximum profitable efficiency the in-service times have to be extended. When loading fibre reinforced polymers (FRP) first damage occurs in the matrix in form of cracks. The crack growth plays an important role and affects the fatigue life of the whole composite. Next to improving mechanical properties of reinforcing fibres and resin systems a comparatively new approach to increase the fatigue life of FRP is the matrix modification with nanoparticles as been published by several authors who tested up to the high cycle fatigue (HCF) regime [1–5]. Even the addition of small amounts of carbon nanoparticles into the epoxy resin matrix improved the LCF and HCF life of fibre reinforced composites by a factor of six to ten. The unique properties of some of these nanoparticles as for example carbon nanotubes (CNT) are used next to the conventional fibre reinforcement to improve the matrix behaviour under cyclic loading. The incorporation of nanoparticles into the matrix increases the fracture toughness as experiments with neat epoxy resin systems revealed. The fracture behaviour like crack growth changes significantly [6–8]. Here, the distribution of the nanoparticles in the FRP plays an important role as agglomerated nanoparticles do not improve the mechanical properties as good as well dispersed ones. The surface area of nano-scaled fillers (1000 m²/g and more) is larger by several orders of magnitude than of conventional fibre reinforcements. The surface area acts not only as an interface for stress transfer it is also responsible for the strong tendency of nanoparticles to form agglomerates as reported by Buschhorn et al [9]. Therefore, when mixing them into the matrix high shear forces are required to obtain a homogeneous dispersion before impregnating the fibres. However, common injection and infusion processes for FRP production like resin transfer moulding have the disadvantage of

filtering the nanoparticles at the reinforcing fibre rovings during impregnation, thus having no homogenous distribution of the nanoparticles over the whole laminate. Additionally, the nanoparticles do not penetrate into the roving and are therefore mainly located in resin rich areas in-between fibre rovings [1]. To get a homogeneous distribution of nanoparticles in FRP it is therefore advisable to use a different impregnation method.

Investigations of fatigue life and damage mechanisms were so far limited to the low and high cycle fatigue (LCF/HCF) regime. The development of reliable fatigue life evaluation methods for FRP at extremely high load cycles ($N > 10^8$) requires a deep understanding of the successive damage behaviour and the occurring damage mechanisms. Common fatigue experiments to gain verified material data with test frequencies up to 20 Hz do not lead to satisfying results within a reasonable testing time. However, higher testing frequencies considerably above 20 Hz can cause extensive warming and undesired premature failure of the specimen as the mechanical properties of epoxy resins change significantly with varying temperature. Above all, fibre reinforced composites show a significant directional degradation of the stiffness and strength during cyclic loading in contrast to isotropic and macroscopic homogeneous engineering materials like metals as already reported by many authors [10,11]. The complexity of the experimental setup and of the damage behaviour of CFRP may be the reason for the lack of well-founded knowledge of the VHCF-fatigue degradation behaviour and appropriate material parameters.

2. Objectives and experimental methods of this work

The aim of this work is to investigate the influence of different types of carbon nanoparticles on the fatigue life and damage mechanisms of CFRP in the high cycle and very high cycle fatigue (VHCF) regime.

2.1 Specimen manufacture

For that purpose unmodified and nanoparticle modified CFRP specimens were produced. Two types of carbon nanoparticles were used: tubular multi-walled carbon nanotubes NC7000 from Nanocyl (Belgium) and few layered graphene avanGraphene-2 from Avanzare (Spain). They differ in size and structure. The carbon nanoparticles were dispersed in the neat resin (without hardener) via shear mixing on a three-roll mill. This method shows good results for dispersing nanoparticles to reduce agglomerate sizes. The nanoparticle amount was set to 0.3 wt% with respect to the resin system.

The FRP were fabricated with an in-house fibre impregnation machine for prepreg production as this method provides good and reproducible nanoparticle distribution within the FRP and penetration of the fibre rovings. In this machine fibre rovings, arranged on a bobbin, get pre-stressed and aligned before being impregnated separately between two rollers with the unmodified or modified resin system. Afterwards the impregnated fibres are winded up next to each other to obtain a unidirectional fibre tape. As fibre reinforcement the commercially available carbon fibre T700S from Toray (Japan) and as matrix the prepreg epoxy resin system Araldite LY 1556/ Aradur 1571/ Accelerator 1573/ Hardener XB 3403 from Huntsman (Switzerland) was utilised. After impregnation the fibre tapes were stored for B-staging according to the resin manufacturers' recommendation. The FRP were laminated in a cross ply lay-up to emphasise the matrix properties.

2.2 Quasi-static loading

To analyse the influence of the carbon nanoparticles on the mechanical properties of CFRP quasi-static tensile tests according to the standards were performed. The tensile strength, strain to failure and the Young's modulus were compared.

2.3 Fatigue loading

For VHCF-testing a new shaker based fatigue test rig as well as adapted test specimens were developed. In the VHCF-test rig the specimens are loaded in flexure which minimises internal shear stresses and with that the polymer specific heating during high frequency fatigue loading. This way, loading frequencies of up to 150 Hz can be performed which is of importance to decrease the extremely long testing time of VHCF tests. Due to the stress distribution under flexural loading it is possible to analyse tensile and compressive fatigue behaviour of the composite simultaneously. Depending on the specimen lay-up different failure modes can be tested separately. Besides that, HCF-tests were performed on conventional uniaxial servo-hydraulic testing machines with a loading frequency of 6 Hz. The sinusoidal loading was applied in the tension-tension regime with R = 0.1.

Unmodified and nanoparticle modified specimen were tested until global specimen failure to investigate the influence on the fatigue life of CFRP. Interrupted tests were performed for all modifications for crack development analysis via ex-situ x-ray measurements. The fracture surfaces were examined by scanning electron microscopy to reveal the influence of nanoparticles on the damage pattern of CFRP and of VHCF-loading in comparison to HCF-loading.

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