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Finite element analysis of an inelastic interface in ultrasonic welded metal/fibre-reinforced polymer joints

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ABSTRACT

The ultrasonic welding technology is an innovative method to produce hybrid joints for multi-material components. In this contribution, the behaviour of an interface layer of metal/fibre-reinforced polymer single overlap tensile specimens is considered. The investigations are carried out using the ultrasonic metal welding technique (UMW) for joining carbon fibre reinforced thermoplastic composites (CFRP) with aluminium alloys. An interfacial traction-separation-law based on elastoplasticity with Lemaitre-type damage is applied. The finite element method is used for the analysis of damage evolution. Two-dimensional interface elements are employed for modelling the solid interface in a 3-D problem. Numerical simulations are carried out for three different interface geometries: square, elongated rectangle and cross rectangle. It is shown that damage develops slower in the specimen with square interface than in the specimen with rectangle interface. The damage parameter reaches the maximum value in every loadstep in the specimen with cross-rectangle interface. Comparison with experimental data shows that the damage process and the fractured zone are identical to simulated results for the specimen with square interface.

1. Introduction

Modern engineering structures in automotive and aerospace industry contain hybrid joints of metals and fibre-reinforced polymers [1]. However, efficient joining methods are necessary to combine dissimilar materials like light alloys and polymer composites in engineering structures. The joints of metal and polymer composites offer a great potential for lightweight design and construction [1,3]. They combine traditional characteristics like strength and ductility with high specific stiffness and physico-chemical resistance of polymer composites [2,4]. At the Institute of Materials Science and Engineering (WKK) of the university of Kaiserslautern ultrasonic metal welding methods were used to realise aluminium alloy/carbon fibre-reinforced polymer (CFRP)-joints. Low temperatures far below the melting point of the metal and low energy inputs as well as short welding times of a few seconds are important features of this solid state welding method. The ultrasonic welding of similar materials, e.g. wires for cable harnesses or plastics for packaging is already established in industrial manufacturing [5]. At the WKK one research aim is to expand the application fields of the ultrasonic metal welding technique by joining dissimilar materials like glass, ceramics or even fibre composites with metals [6].

Practically, there are three parts in the specimen of a UMW joint: the polymer composite (matrix and fibre reinforcement), the metallic partner and an interface material in the welding zone of the specimen. The simulation of such modern engineering structures is an economical imperative.

The size of the interface layer and its parameters have a large impact onto the mechanical behaviour of the entire joint. The finite element method (FEM) is used for the investigation of so-called interface elements and the bulk specimen [7,8].

By application of adequate physical models and subsequent mathematical treatment, several benefits are achieved [9]. The number of experiments can be reduced and a prediction of the mechanical behaviour of structures is possible. This research aims at the investigation of the mechanical behaviour of interface layer in tension metal/fibre-reinforced polymer specimen.

2. Materials, ultrasonic welding technology and model of the specimen

2.1. Experimental investigation

The experimental investigations described in this paper are carried out using UMW to join sheet metals to carbon fibre-reinforced

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Table 1
Mechanical properties of AA5754 and CF-PA66 sheets.

Material	Young's modulus (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Ultimate strain (%)
AA5754	70	177	250	13.5
CF-PA66	55	/	580	1.1

thermoplastic composites. One great advantage of an ultrasonic oscillation parallel to the surface of the joining partners is the possibility of a direct contact between the load bearing fibres of the reinforced composite without destroying the carbon fibres. Scanning electron microscopy (SEM) of the welding zones has shown that the ultrasonic metal welding technique removes the matrix between the fibre reinforcement and the metal. So the metallic surface gets into direct contact to the fibres [1,9].

In the following selected results for the tensile behaviour of welded single overlap specimen between the aluminium alloy 5754 (AA5754) and CFRP sheets are presented. For the aluminium sheet a thickness of 1 mm and for the CFRP 2 mm are chosen. The fibre reinforcement of CF-PA66 is a C-textile Satin 5H-fabric with a weight per unit area of 285 g/m^2. The fibre volume fraction of the 2 mm thick organic sheets is about 48%. It was manufactured in an autoclave process by using six layers of CF-fabric. Selected mechanical properties are summarized in Table 1 [3].

The specimen geometry is given in Fig. 1a. The welding area of the square sonotrode is 10 mm × 10 mm (sonotrode coupling face). Furthermore the welding system is shown in Fig. 1b. Besides a high reproducible clamping of the specimens, it is necessary to control the welding force during the joining process precisely by an integrated force measuring device.

Suitable combinations of the three welding parameters (welding force, oscillation amplitude and welding energy) were evaluated by statistical test methods and proved in tensile shear tests. Tensile shear strengths of more than 30 MPa were determined for suitable process parameters for AA5754/CF-PA66-joints. The application of off-peak staged welding force profiles enables higher tensile shear strengths of up to 45 MPa. An additional metal pretreatment by a corundum blasting process or acid pickling in concentrated nitric acid leads to a further increase to 54 MPa and to a positive effect on the long-term stability of the metal/CFRP-joints [1]. For each parameter combination 12 welds were performed. Despite the sensitivity of the carbon fibre-reinforced composite it was possible to identify welding parameter combinations which lead to stable joints.

In addition to the experimental use of a square sonotrode, Fig. 2b and c contains the specimens with the elongated rectangle and cross rectangle interface geometries correspondingly, which are only used for computational investigations.

2.2. Computational model

The material AA5754 is simulated as an isotropic elastoplastic material. The polymer composite CF-PA66 generally shows an orthotropic elastic behaviour [10]. The geometry of the specimen is depicted in Fig. 2. The interface material lies directly in the welding zone of the specimen. The geometry of the interface area is a direct consequence of the sonotrode geometry. Fig. 2a shows a specimen, produced with use of a square sonotrode. Fig. 2b and c contains the specimens with the elongated rectangle and cross rectangle interface geometries correspondingly. The interface material has been numerically modeled as an elastoplastic material with linear hardening, coupled to Lemaitre-type damage [7,11].

An elastoplastic bulk material law with isotropic hardening is used to model the aluminium plate [12,13]. The total strain $\boldsymbol{\varepsilon}$ is split by

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^e + \boldsymbol{\varepsilon}^p,$$

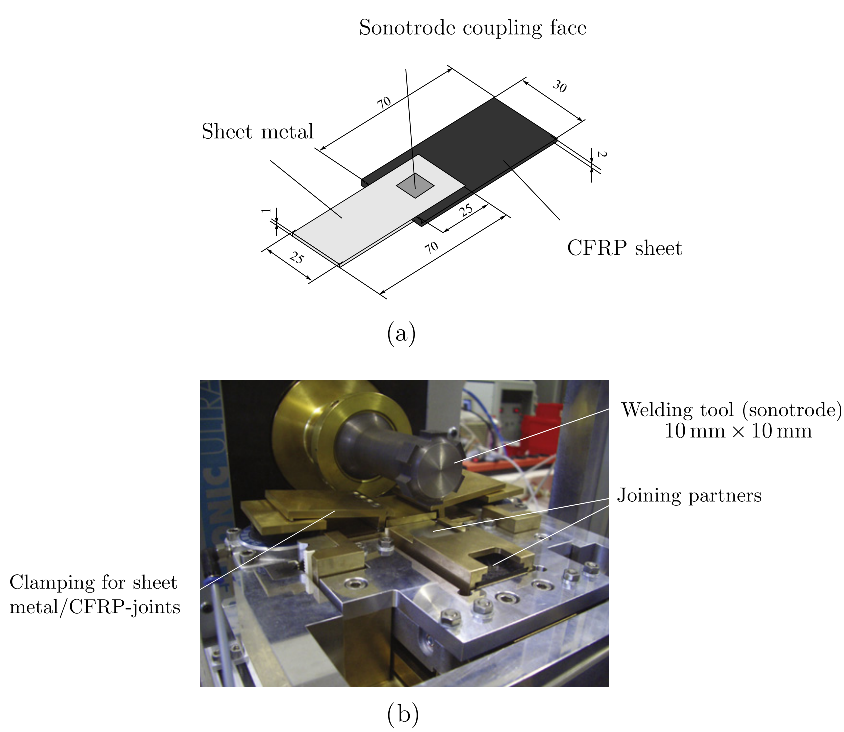

Fig. 1. (a) Specimen geometry (square interface), (b) ultrasonic spot welding system.