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The effect of protrusion density on composite-metal joints with surfi-sculpt reinforcement

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ABSTRACT

The effect of protrusion density on the static mechanical properties of composite-metal joints strengthened by surfi-sculpt protrusions has been experimentally studied with single lap joints. The CFRP composite adherends were constant thickness with a quasi-isotropic layup. The metallic adherends were Ti-6Al-4V alloy with a variable number of protrusions per unit area, manufactured by electron beam surfi-sculpt. Digital image correlation was used to measure the debonding on the overlap during the tests. Although the surfi-sculpt protrusions did not significantly affect the onset of debonding, they did resist the initial unstable failure mechanism and converted it into stable growth. The analysis indicated that the efficiency of the surface protrusions was different at the metal and composite ends of the overlap. This finding opens the possibility to vary the protrusion density across the overlap to meet specific damage tolerance criteria and optimise joint efficiency. Increasing the protrusion density significantly increased the ultimate failure load, joint extension and hence absorbed energy.

1. Introduction

Joining dissimilar material such as carbon fibre reinforced plastic (CFRP) to metals effectively has been a significant challenge. The most common joining technologies are adhesive bonding and mechanically fastened joints. For bonded joints, adhesive bonding is usually sensitive to surface preparation and many such joints are limited in use to secondary loading applications due to their relatively low strengths. Moreover, inspection of the bond-line in service is also difficult. The subsequent failure of bonded joints is usually abrupt and catastrophic. For mechanically fastened joints, there is a need for holes to be formed in the composite and the intrinsic brittleness of CFRP makes them sensitive to these stress concentrations [1]. The use of mechanical fasteners therefore reduces structural integrity and also increases the weight, offsetting the potential weight saving gained from using the composite.

An innovative joining technology known as Surfi-Sculpt adopts the idea of z-pinning technology in a composite-composite joint by creating arrays of macro-scale surfi-sculpts on the surface of metal part. This allows a mechanical joint to form between the metal and the composite without the need for holes [2]. This advanced hybrid joint thus combines the advantages of a bonded and mechanically fastened joint. In this work, the electron beam surfi-sculpt (EBS) technique has been employed to create protrusions on the metal adherends using a process that uses multiple relative movements between an electron beam and the metal surface [3,4]. Although some studies on the mechanical properties and damage tolerance of joints formed using this technology have been reported [5–14], little has been reported on the effects of protrusion density in hybrid joints.

The purpose of this study is to evaluate experimentally the effect of surfi-sculpt protrusion density on the mechanical properties of composite-metal joints strengthened by surfi-sculpt. Four joint types with different surfi-sculpt protrusion densities together with a reference joint have been tested and the initial damage, ultimate failure, debonding propagation and absorbed energy have been compared.

2. Single lap joint manufacture

The single lap joints, as shown in Fig. 1, has been adopted in the present work. Although single lap joints introduce normal stresses at the ends of the overlap which affects the apparent shear strength of the joint, they are easy to manufacture and hence are

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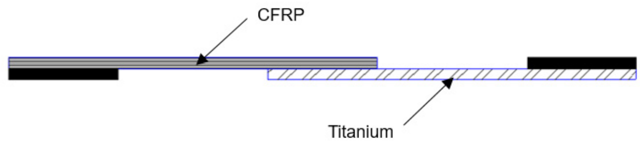

Fig. 1. Single lap joint.

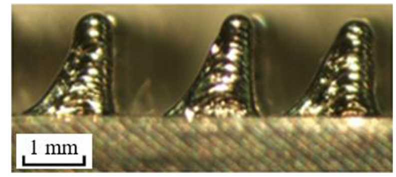

Fig. 2. Surfi-sculpt protrusions.

widely used [15]. Moreover, this manufacturing ease leads to joints with higher quality and greater reliability than using double lap joints to achieve a desired joint shape [10]. Single lap joints provide more freedom for composite layup design (stacking sequences) and are convenient for damage growth detection [12].

The objective of this study is to investigate the effect of the surfi-sculpt protrusion density on the static mechanical properties of the advanced hybrid joints. The test matrix studied is shown in Table 1. Four types of joint with different surfi-sculpt protrusion densities were tested. Unstrengthened joints were also manufactured and tested as reference. For each type of joint, at least two specimens were tested.

2.1. Materials

Ti-6Al-4V [4,16] was used to manufacture the metal adherend. This alloy is frequently used in the manufacture of hybrid (metal-CFRP) structures in aerospace applications. The composite used to manufacture CFRP adherend was a hot-melt, epoxy prepreg SE 84LV [17]. The fibre of the prepreg is RC200T which is a woven fibre.

Electron beam surfi-sculpt (EBS) was adopted to manufacture surfi-sculpt protrusions on the bonding surface of the metal adherends [3,4]. The electron beam impacts the metal surface through a special track. The external metal on the track is melted and this molten metal is displaced due to surface tension and vapour tension forming a projection [18]. After a portion of the molten metal solidifies, the EB scan is repeated one or more times. Desired protrusions can be formed with special tracks and using the optimized processing parameters of the EB. Fig. 2 shows the surfi-sculpt protrusion shape obtained for the present work.

2.2. Joint manufacture

The integration of the metal and composite adherends was completed using vacuum bag processing [17]. Before the vacuum bag processing, the full thickness of the CFRP adherend was built up using the required number and sequence of prepregs (Table 1) and this was placed onto the metal adherends. During the vacuum bag processing, the protrusions were pressed into the uncured laminate with the pressure provided by the vacuum bag. The assembly was finally co-bonded on a hot plate, after which the composite was trimmed to size. Bespoke tooling was used to ensure thorough consolidation of the CFRP matrix and to minimise any misalignment between the laminate and the metal adherend. The lap joints manufactured had a width of 25.4 mm and a nominal overlap length of 30 mm.

The insertion of the surfi-sculpt protrusions into the composite introduces resin rich zones and can cause some fibre damage, as shown in the scanning electron micrograph in Fig. 3. To prevent the resin rich zones joining together the distance between two adjacent protrusions in both the horizontal and vertical directions was carefully controlled. Every other row of protrusions was offset by a distance equal to half the inter-protrusion distance along the row direction. Taking joint 'DEN1' for example, the final surfi-sculpt protrusion array design of joint DEN1 is shown in Fig. 4, and contains three rows of 5 protrusions and three rows of 6 protrusions, giving 33 protrusions in total over the overlap area. As the bonding area and the protrusion distribution pattern of all strengthened joints were nominally the same, the surfi-sculpt protrusion number (i.e. number of protrusions on the overlap) is used to represent the corresponding surfi-sculpt protrusion density in this paper.

3. Experimental

Single lap shear tests were conducted under displacement control on an Instron testing machine (model 3369) at ambient temperature. The cross head rate was 0.3 mm/min. This is a much lower rate than specified in ASTM D5868 [19] to allow for smaller changes in the compliance of the joint to be recorded. Prior to loading, an extensometer with a gauge length of 50 mm was attached to the specimen as shown in Fig. 5. During the tests, the extension of the gauge length was recorded. DIC (Digital Image Correlation) [20] was also employed on the lateral side of the joint to identify the occurrence and the evolution of the debonding of the joint.

4. Results and discussion

4.1. Load-displacement behaviour

Fig. 6 compares the typical load-displacement curve measured for the reference joint (control- no protrusions) with the curves for the strengthened joints manufactured with four different protrusion densities (DEN1 to DEN4).

The curve of the reference joint rises linearly up to 4 kN, at which point the stiffness of the joint experiences an abrupt change due to the initiation of debonding. The load at this point is referred to as the damage initiation load. The joint is then further damaged by unstable debonding after a further small increase in load (about 200 N). The resulting debonding propagates rapidly and the joint fails catastrophically because the joint geometry under the tensile

Table 1
Test matrix.

Joint type	CFRP nominal thickness (mm)	Composite layup	Surfi-sculpt array	Number of Protrusions	Joint No.
Reference	2.6	$[45/0]_3/45/\ [0/45]_3$	no surfi-sculpt	0	R
Protrusion density effect	2.6	$[45/0]_3/45/\ [0/45]_3$	5, 6, 5, 6, 5, 6	33	DEN1
		$[45/0]_3/45/\ [0/45]_3$	6, 7, 6, 7, 6, 7, 6, 7	52	DEN 2
		$[45/0]_3/45/\ [0/45]_3$	7, 8, 7, 8, 7, 8, 7, 8	60	DEN 3
		$[45/0]_3/45/\ [0/45]_3$	9,10,9,10,9,10,9,10,9,10	95	DEN 4