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Fatigue behaviour of titanium/PET joints formed by ultrasound-aided laser welding

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ABSTRACT

The fatigue properties of metal/plastic hybrid joints are an important engineering consideration. There are only few studies on this subject are available, but none was found on studying the fatigue behaviour of laser welded metal/plastic joints. The objective of this study is to characterise and to compare the fatigue performance, in terms of S-N data, of the lap joined Ti/PET hybrid specimens produced by laser welding with and without ultrasound aiding. The fatigue resistance, in terms of S-N data, of the joints formed with the aid of ultrasound was always higher than that of those joints produced without using ultrasound, and the improvement was at least one order of magnitude higher when compared to the same laser processing condition. The fatigue resistance of these two kinds of joints can be explained by the proposed fatigue crack propagation paths, which are closely associated to the porosity in the joint zone and the chemical bonding at the joint interface. For the specimens formed with the aid of ultrasound, a stronger chemically bonded joint interface was obtained, and this increases the fatigue life of the joint. With a similar chemical bonding nature, an improvement of fatigue life of one order of magnitude was attained when porosity was eliminated from the joint zone.

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1. Introduction

In engineering and product design, especially in the automotive [1] and biomedical industries [2], there has always been great interest in joining dissimilar materials, such as metals and plastics. In order to obtain a strong hybrid metal-plastic joint, a variety of techniques have been developed, such as induction [3] and ultrasonic [4,5] welding, laser-assisted metals and plastics joining (LAMP) [6,7], friction-based lap welding and spot joining [8–10]. Among these, both the LAMP and friction-based methods produce bubbles in the bond area due to decomposition of the plastic material. For LAMP, the laser light transmitted through the plastic part heats up the metal surface at the joint interface and consequently causes melting and decomposition of the plastic [6]. As a result, laser-induced bubbles are produced, which on the one hand, assist in creating an intimate contact surface between the metal and plastic parts by inducing high pressure in the molten plastic [6,11], but on the other hand are themselves defects by nature, and therefore have a counter effect on the joint strength [12–14].

Recently, Chen et al. [15] developed a new ultrasound-aided laser joining method (U-LAMP) – using the conjoint action of a laser and ultrasonic (Fig. 1) – that has been shown to be superior to LAMP. The benefit of the new process has been demonstrated by a study of joining polyethylene terephthalate (PET) to pure titanium (Ti), under a low laser power condition. Using a low laser power avoids decomposition of the polymer and the formation of a large number of bubbles, and the action of ultrasonic vibration causes intimate contact between the molten PET and Ti metal, which results in a strong chemical bond at the joint interface. The joint produced using ultrasonic aiding, in terms of tensile failure load, was always higher than that of the joint formed without any ultrasound aiding. The improvement can be as high as three times. Building on this success, Chen et al. [16] further developed U-LAMP to address the laser-induced bubble problem, with the aim of reducing bubbles at the plastic-metal joint interface when relatively high laser powers are used. A series of experiments verified that in using U-LAMP with an appropriate transducer tool, the number of bubbles was significantly reduced and in most cases no sizable bubbles could be observed under an optical microscope. These previous papers have reported the principles of U-LAMP and the mechanism of

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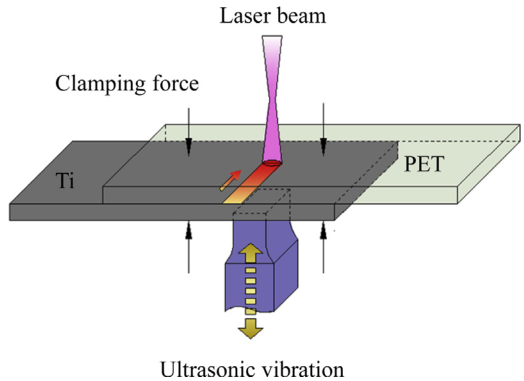

Fig. 1. A schematic diagram showing the U-LAMP method.

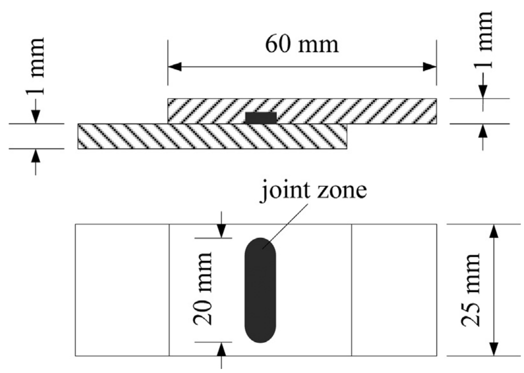

Fig. 2. The dimensions of the lap joint.

ultrasound in driving bubbles away from the joint zone, the tensile properties as well as the nature of the chemical bonds at the joint interface [15,16].

A literature search revealed that the fatigue properties of metal/plastic hybrid joints have not been well studied and only a few studies were found [17–19], which were mainly confined to adhesive bonding. It was generally found that fatigue cracks propagated along the adhesive/plastic interfaces [18,19]. With regard to adhesive bonding, defects, such as voids present within the adhesive layer [20–22], and the adhesive thickness [23,24] have significant effects on the fatigue life of the joint. Turning to the LAMP and U-LAMP joints, where no adhesive is involved, the thickness of the interface containing new chemical bonds between the metal and polymer is only about 1–2 μm [15,16], which is considered to be small when compared to the case of adhesive bonding. It is envisaged that the fatigue behaviour of LAMP and U-LAMP joints is different from that of adhesive bonded joints. However, there are sparse studies on the fatigue properties of metal/plastic hybrid joints formed by laser processing. This paper reports some preliminary fatigue results of lap joined specimens produced by the traditional LAMP and the newly developed U-LAMP methods.

2. Experimental method

The principles of LAMP and U-LAMP, details of the experiment set-up and the procedures for ultrasound-aided laser joining of Ti sheet (ASTM B265 Grade 1) to polyethylene terephthalate (PET) sheet, can be found in previous publications [15,16]. The PET and Ti specimens for laser joining had dimensions of 60 mm × 25 mm × 1 mm (Fig. 2). The surface of the Ti specimens was ground finished with emery paper (#1200) to remove oxide films from the surface, and all the PET and Ti specimens were ultrasonically cleaned in an ethanol bath before joining. The joint

Table 1
Designation of specimens.

LAMP (Without ultrasonic vibration)	LP_30W_UA_0	Specimen A
	LP_55W_UA_0	Specimen B
U-LAMP (With ultrasonic vibration)	LP_30W_UA_4	Specimen C
	LP_55W_UA_4	Specimen D

LP = Laser power (W).
UA = Ultrasonic vibration amplitude (μm).

Table 2
S-N data of the LAMP and U-LAMP specimens.

Specimens	Designation	Fatigue life (cycles)				
		Test 1	Test 2	Test 3	Test 4	Test 5
LAMP_30 W	Specimen A	3078	2856	2538	2246	1982
LAMP_55 W	Specimen B	186542	154896	102886	98652	46326
U-LAMP_30 W	Specimen C	>600000	567894	511836	386604	268956
U-LAMP_55 W	Specimen D	2177962	>600000	>600000	586184	548764

specimens were produced using laser powers of 55 W and 30 W, with and without ultrasonic vibration, while other joining parameters were kept constant. These two laser power conditions were chosen because the fatigue properties of the specimens, with porosity and without obvious porosity, can be compared. The condition of 55 W was chosen because this condition yielded the maximum shear failure load, while for the case of 30 W, both the LAMP and U-LAMP specimens were largely free from porosity [15,16]. Details of the production of these specimens can also be found in references [15,16]. The designation of specimens is listed in Table 1. Fig. 3 shows the joints of these four types of specimens for ease of reference. When the laser power was low, i.e. at 30 W, both the LAMP and U-LAMP specimens (Specimens A and C) are free from porosity; while at high laser power, i.e. 55 W, LAMP Specimen B has porosity but U-LAMP Specimen D is largely free from porosity. The tensile shear properties of these four types of specimens have been reported previously [15,16].

To compare the fatigue properties of the LAMP and U-LAMP joined specimens at room temperature conditions, load-controlled fatigue tests were performed using a servo-hydraulic MTS machine (810 Material Test System) to obtain S-N fatigue curves. The specimens were fatigue-tested using a tensile sinusoidal load with mean stress 200 N, load ratio (R_{load}) 0.25 and frequency (f) 2 Hz. The test was stopped when the specimen failed or if a specimen survived more than six hundred thousand cycles. The S-N results obtained were correlated with observations derived from light and scanning electron microscopy (SEM) studies of the joints after fatigue testing. X-ray photoelectron spectroscopy (XPS) was utilized to obtain information on the chemical bonds at the Ti/PET interfaces. High-resolution spectra were recorded by using a pass energy of 58.7 eV. The analysis was conducted in a semi-quantitative mode, and the XPS data were fitted by using the curve-fitting program of the XPS-PEAK software.

3. Results and discussion

3.1. S-N data

The S-N data of all the specimens are summarized in Table 2 and are presented in Fig. 4. The results show that the fatigue resistance of the specimens follows the sequence of U-LAMP_55 W > U-LAMP_30 W > LAMP_55 W > LAMP_30 W. In the absence of porosity in the U-LAMP joints, increasing the laser power from 30 W to 55 W results in a longer fatigue life. For the LAMP specimens, although the LAMP_55 W specimen has porosity, its fatigue resistance is still better than that of LAMP_30 W which is free from porosity. It has been found that LAMP_55 W has a greater chemical bond at the

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