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Friction Assisted Joining of titanium and polyetheretherketone (PEEK) sheets

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ABSTRACT

Friction Assisted Joining process of titanium and Polyetheretherketone sheets is investigated. Laser texturing was previously performed on the titanium sheets to promote the mechanical joining between the substrates to increase the strength of the joints. Infrared thermography was conducted by means of an IR camera to measure the temperature trend and distribution during the joining process. Quasi-static single lap shear tests were performed to determine the influence of the processing conditions on the strength of the joints. Morphological analysis and fracture surface analysis were conducted to understand the influence of the energy supplied on the quality of the joints. The joints with the highest strength were achieved after the minimum heating time 7.5 s. These joints where characterized by a shear strength of 37.3 MPa corresponding to 66% of that of the PEEK material. Longer heating times resulted in severe thermal degradation (carbonization) of the polymer in the central region, which was due to the low thermal conductivity of the titanium. Nevertheless, the Ultimate Shear Force continuously increased with the heating time up to 8.85 kN (for heating time of 25 s) due to the increase in the joined area.

1. Introduction

Multi-materials components involving metals, polymers and composite materials are increasingly employed in several fields and applications including structural, transportation as well as biomedical ones [1]. However, joining such materials that usually show different mechanical, thermal and physical behaviors introduces several limitations and concerns. Thus, given the high demand from different production fields, great efforts are being spending in order to overcome the main limitations and disadvantages of traditional joining processes such as mechanical joining and adhesive bonding. These processes are characterized by remarkable problems in terms of stress concentration, damage, employment of costly and heavy external components (mechanical joining), as well as long term strength, environmental sensitivity, environmental impact, energy efficiency (adhesive bonding). Both these joining process categories show also productivity issues as predrilling and curing time are required, respectively. To this end, different joining processes have been developed in the recent years in order to overcome the aforementioned issues. Among them, mechanical joining processes such as self-pierce riveting [2] and clinching [3,4] as well as heat assisted joining processes such as Injection Joining [5] Laser Assisted Joining (LAJ) [6] and Friction Assisted Joining (FAJ) [7], which is very similar to Friction Lap Welding [8] Friction Spot Joining [9] and Ultrasonic Joining [10–12], have been widely employed to join metals, polymers and composites.

The latter processes produce a tight connection between the substrates. During the process the interface is heated directly (as in the case of LAJ exploiting the polymer transparency to the laser wavelength) or by conduction (generally when the polymer has to be joined to metals). Thus, the thermoplastic polymer is heated up to melting (or softening) and it is forced against the metal or also composite laminates [13] to achieve the aforementioned joining conditions. Thus, chemical (mainly CO bonds), physical (mainly van der Waals forces) or mechanical joining can be achieved. In addition, despite common joining processes based on diffused heat sources e.g. hot plate welding, hot bar welding, hot gas welding, etc., LAJ and FAJ exploit confined heat sources that result in high process efficiency, and reduction of the joining time. During Laser Assisted Joining a laser source is moved along a path to produce spot or continues joints; thus an external clamping force is required [6]. The process has been successful employed for a wide range of metals and polymers. Recent developments demonstrated the feasibility for joining composites with thermosetting matrices to thermoplastics [13,14] as well as techno-polymers such as PEEK [15].

Conversely, FAJ exploits friction generated by the rotation of a tool

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which is plunged against the upper sheet (generally a metal sheet). Thus, the contact pressure is given by the vertical force exerted by the tool. Different studies have been conducted to fully understand the joining mechanism, that of the formation of porosities [16] as well as to functionalize the surfaces before joining. To this end, different pretreatments were proposed including grafting [17] anodization of the metal substrate [18–20] formation of both macroscopic [21] and microscopic structures on the metal substrate [22]. These pretreatments were mainly aimed at increasing the bond strength [23] including promotion of CO bonds and increase in mechanical interlock. Other modifications were also proposed to reduce the formation of porosities e.g. by the adoption of ultrasonic aided systems [24].

The joining conditions depend, among the others, by the thermal and mechanical characteristics of the substrates to be joined. Although, a number of studies have been conducted involving high strength polymers, and composite laminates (with both thermoplastic and thermosetting matrix), a few studies have been performed involving techno-polymers such as that reported in [25], where aluminum alloy AA5053 sheets were coupled to polyetheretherketone (PEEK). That study revealed that great mechanical strength can be achieved with a maximum shear strength of 47 MPa. In the present study, the feasibility of joining titanium grade 2 and PEEK by means of FAJ is studied experimentally. These materials are of particular interest as their high strength to weight ratio and biocompatibility that are particularly interesting in different fields including aeronautic, aerospace but also for production of biomedical prosthesis. In addition, the thermal behavior of the titanium as compared to that of the aluminum used the above-mentioned work should involve very different thermal conditions and consequently highly uneven morphology is expected when joining titanium by FAJ process. Thus, the work investigates how the morphology of these joints is affected by the supplied energy and thermal field. In addition the mechanical performance is investigated to determine a sound technological window and main phenomena characterizing FAJ of these materials.

2. Materials and methods

2.1. Specimens preparation

Rolled sheets with 2 mm thickness of titanium alloy Grade 2 were joined to polyetheretherketone (PEEK) supplied by Victrex (PEEK 450 G) with 5 mm of thickness. PEEK (polyetheretherketone) is a semi-crystalline thermoplastic with a service temperature up to 250 °C and melting temperature of 343 °C.

Mechanical characterization of the base material was performed by conducting tensile tests according to ASTM E08 [26] and ASTM D638 [27] (Type 4) standards for the titanium and PEEK, respectively. Thermogravimetric tests were conducted to investigate the decomposition temperature of the PEEK material by means of a machine model L81/1550 by LINSEIS. The tests were conducted at the highest heating rate allowed by the machine 40 °C/min. The main mechanical and thermal properties of the materials are summarized in Table 1.

The chemical composition of the titanium sheet was determined by means of X-ray fluorescence spectrometry (XRF) technology. To this end, a XRF machine model XEPOS III by Spectro. Table 2 summarized the chemical composition of the titanium.

Before joining the materials were cleaned in an ultrasonic bath (water and ethanol) to eliminate rests of oils, grease and powder. Some preliminary tests were performed without the texture but the joints had negligible strength. Thus, laser texturing was performed on the titanium surface to produce micro-teeth and consequently improve the mechanical fastening between the substrates. To this end, a 30 W fiber laser (YLP-RA30-1-50-20-20 by IPG) was adopted. A square-net path was used with the following processing conditions: average power 30 W, pulse frequency 30 kHz, scanning speed 1000 mm/s, hatch distance (i.e. the distance between two consecutive lines) 0.3 mm, and 40 repetitions for each path. The texture produced on the titanium sheet surface was positioned against the upper PEEK surface, as also shown in Fig. 1. The texture was performed to cover all the interface region (square area 20 mm × 20 mm).

Table 2
Chemical composition of the titanium sheet.

Element	Ti	Fe	Al	Ca	Ni	Zn
% Weight	98.90	0.01759	0.02098	0.04846	0.01593	0.00055

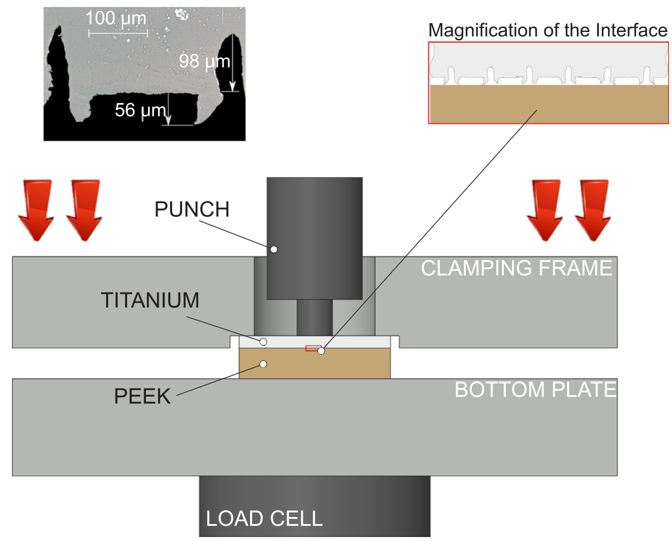

Fig. 1. Schematic representation of the adopted setup.

2.2. Joining procedure

Friction Assisted Joining was performed by using an instrumented CNC drilling machine, which is described in detail in [28]. The machine was equipped with a retrofit system that enabled to perform the FAJ by means of displacement as well as load control. To this end, the machine is equipped with a two-component (F_z–Plunging force, M_z–torque) piezo-electric cell by Kistler and a position transducer. The experimental tests were performed under controlled constant plunging force F_z = 320 N (that corresponded almost to 60% of the machine capacity) and constant tool rotational speed ω = 5400 rpm. A cylindrical tool with an end tip diameter of 6 mm, long 5 mm and with a shoulder of 10 mm diameter, made of hardened K340 by Boheler high strength steel was used in all the tests. This material has the following elements as the main alloy element: C (1.10%), Si (0.90%), Mn (0.40%) Cr (8.30%) Mo

Table 1
Main mechanical properties of the materials.

Material	Young Modulus [GPa]	Yield Strength $\sigma_{y0.2}$ [MPa]	Tensile Strength, σ_{max} [MPa]	Compressive Strength [MPa]	Elongation at rupture [%]	Melting temperature [°C]	Thermal decomposition temperature [°C]
Titanium	120	394	450	–	20	1670	–
PEEK	4		98	125	45	343	520