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Effect of the friction riveting process parameters on the joint formation and performance of Ti alloy/short-fibre reinforced polyether ether ketone joints

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ABSTRACT

The feasibility of friction riveting on short carbon fibre-reinforced thermoplastic polymers was investigated in this work. A design of experiments (DoE) was used to investigate the impact of rotational speed, friction time, friction pressure and forging pressure on joint formation and performance. The joint formation was studied using the mushrooming efficiency, the rivet penetration depth and the mechanical energy input. The tensile pull-out force was used to describe the mechanical performance of the investigated metallic-insert joints made of grade 3 titanium and short carbon fibre-reinforced polyether ether ketone (PEEK). All samples were scanned with X-rays before any mechanical testing to acquire the dimensions of the anchored rivet inside the reinforced polymer, elucidating their correlations with the mechanical performance. The DoE model can be used to tailor joint formation and performance. A parameter-set that improves the pull-out performance was determined using an analysis of variance. The analysis revealed that high rotational speed, friction time and forging pressure caused high pull-out forces. The metallic-insert joints reached high pull-out tensile strength between 6.3 kN and 10.7 kN. The dimensions of the deformed metallic rivet were correlated with the mechanical performance of the joint: the larger the widening of the rivet tip, the higher the pull out force was. Furthermore, widening of the rivet tip by 70% led to the maximal tensile pull-out force (10.7 kN), corresponding to the base material strength of the titanium rivet (10.7 kN). At this threshold value (70%), the failure mode also changed from failure mode III (pull-out of rivet) to failure mode I (rivet failure).

1. Introduction

In recent years, the use of thermoplastics with and without fibre-reinforcement has increased significantly within the transportation industry, such as in automotive and aircraft structures, or in other high performance engineering applications, such as wind-energy engineering, sporting goods and medical appliances [1]. Using thermoplastic composites is advantageous because of their high fracture toughness, better environmental resistance and recyclability [1–3]; however, one of the main reasons for moving from a purely metallic structure toward composite multi-material structures is the possibility to tailor their performance according to the structural requirements [3,4].

The increasing presence of thermoplastic parts in large structural components requires adequate joining techniques for multi-material structures [5]. Currently, thermoplastics and reinforced thermoplastics can be joined using different techniques. These joining techniques can be divided into three main groups: mechanical fastening, adhesive bonding and welding [5–9]. The design of large complex structures that incorporate new materials generates new material combinations that require new joining technologies [4,10].

Some recent and less-explored joining technologies have become available for joining thermoplastic composites, such as induction- and resistance welding or laser bonding. These joining technologies use the properties of the thermoplastic matrices to be reheated or remelted and consolidated repeatedly [11–13].

One alternative joining technology is friction riveting; a friction-based spot joining process developed for joining thermoplastic-lightweight alloy structures that was first patented by Helmholtz-Zentrum Geesthacht [14,15]. Friction riveting bridges the gap between mechanical fastening and welding, offering advantages including short joining cycles and limited surface

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pre-treatment of the joining partners; this method also reduces the number of installation steps by eliminating pre-drilling [16].

Earlier studies of friction riveting (FricRiveting) using unreinforced polyetherimide (PEI) and aluminium AA2024 [16,17] have successfully demonstrated the feasibility of metallic-insert joints. A study has been already carried out to describe the influence of a single FricRiveting process parameter, the rotational speed on the joint microstructure, the local and global strength and the thermal history [18,19], but no research was found describing how to tailor mechanical performance or to apply advanced design of experiments and statistics to analyse the correlation between the relevant process parameters and the joint performance.

Design of experiments (DoE) is a powerful statistical tool used to optimise welding and joining processes. When coupled with an analysis of variance, the DoE elucidates the influence of the joining process on joint characteristics. The welding process parameters and the tool geometry affect the properties of friction stir spot welded high density polyethylene sheets, as indicated by Bilici et al. [20,21]. These researchers investigated the effects of the rotational speed, plunge depth, plunge rate and dwell time of the tool on the joint lap-shear strength. By applying a “one-factor-at-a-time” approach, this group found that the rotational speed, plunge depth and dwell time were important when optimising the ultimate lap-shear strength. The dwell time and the rotational speed significantly influenced the lap shear strength because increasing the dwell time or rotational speed increased the frictional heat and enlarged the welded areas. The authors observed that increasing the plunge depth led to increased frictional heat generation and welded areas up to a threshold value; after exceeding this value, the lap shear strength decreases due to the thinning of the upper plate of the joint. The authors found that the pin angle, shoulder diameter, shoulder concavity angle and tool geometry significantly affect the weld strength because they all influence the nugget thickness, allowing them to modulate the failure mode and the joint strength. Harras et al. [22] studied the effect of process parameters using a “one-factor-at-a-time” approach to determine the optimised welding conditions for ultrasonic welding with poly(ether-ether-ketone) (PEEK)–carbon composites. They investigated the effects of pressure and welding time on the modes I and II fracture performance of the joints; 3.8 MPa with an energy input of 6.8 J/mm^2 showed the best results for both of the tested modes.

This work applies this new joining technology to short fibre-reinforced thermoplastic materials and titanium. This investigation describes the influence of the process parameters on joint formation and performance. A better understanding of these effects may enable joint formation and performance to be tailored according to the requirements of the potential engineering applications. DoE was used to investigate the effect of the process parameters on the formation and performance of short carbon fibre-reinforced PEEK/commercially pure titanium grade 3 metallic-insert joints. The correlations between the process parameters and the mechanical performance of the joint were evaluated, and a set of optimised joining parameters was determined, resulting in joints with high tensile strength at levels comparable to tensile strength of the rivet base material. In addition, regression equations were developed for each response, showing high accuracy levels when predicting the responses. This work includes a discussion of the observed failure modes and their relationship to the geometry of the deformed titanium rivet.

2. The friction riveting process

This process is best explained using the simplest friction riveted joint: a “metallic-insert” joint composed of a metallic rivet anchored inside a thermoplastic base plate. This process has been introduced by Amancio et al. [9,16–18,23,24]; this group investigated the friction riveting process using un-reinforced plastics and aluminium. The major process steps are described in Fig. 1. First, the two joining partners are fixed in the joining equipment with the thermoplastic base plate placed onto the backing plate and the titanium rivet placed in the spindle. Subsequently, the rivet begins to rotate, moving toward the thermoplastic base plate and finally touching it (Fig. 1b). The combination of rotation and axial pressure generates frictional heat, forming a thin layer of molten polymer around the rivet tip. Because the rivet is continuously fed during the friction phase, molten material is partially expelled, forming a flash. The heat generation rate during this phase increases, and the heat input grows to exceed the heat outflow due to the extremely low thermal conductivity of the short carbon fibre-reinforced PEEK and titanium rivet. Due to the local increase in temperature, the rivet tip becomes plasticised. At this point, the motor brake activates, decelerating the spindle rotation; an additional pressure called the forging pressure (FoP) is concomitantly applied (Fig. 1(c)). The molten polymer layer below the rivet tip is suppressed by the additional axial pressure, and the tip of the rivet is forged backwards by the revealing solid region. This forging step widens the rivet tip, creating an inverted parabolic pattern (i.e., mushroom-like shape or geometry). During the last step (Fig. 1(d)) the joint consolidates and cools under a constant external pressure, while the rivet remains strongly anchored in the polymeric plate, forming a metallic-insert joint.

3. Materials and methods

3.1. Base materials

The metallic-insert joint geometry investigated in this study was manufactured using two parts: a short-fibre reinforced polymeric base plate and a metallic rivet (Figs. 2 and 3). The thermoplastic composite material used to fabricate the polymeric base plate was poly(ether-ether-ketone) (PEEK) reinforced with 30% by weight short carbon fibres (Ketron® PEEK-CA30, Arthur Krüger, Barsbüttel, Germany). The base plate geometry and dimensions (70 × 70 × 21 mm) are shown in Fig. 2a. PEEK is a high performance semi-crystalline thermoplastic polymer [25–28]; short carbon fibre-reinforced PEEK is often selected for its excellent wear resistance and good mechanical performance at elevated temperatures [28]. Fig. 2b presents the microstructure of the polymeric base plates. The relevant properties of the PEEK composite used for this work are compiled in Table 1. This composite is used in the aerospace, automotive, chemical and medical industries [26,28].

The rivets were made from extruded and commercially pure titanium grade 3 with length of 60 mm and a diameter of 5 mm. The geometry and a macrograph of the base material are shown in Fig. 3. Grade 3 Ti contains only one phase: the alpha phase. Fig. 3b shows the microstructure parallel to the extrusion direction, revealing equiaxed alpha grains and some twins. This grade of commercially pure titanium is often used for its excellent corrosion resistance and fairly good strength to weight ratio; this material is often utilised to bridge design gaps between aluminium and steel [29]. The strength of grade 3 titanium is comparable to the strength of aluminium 2024, which is typically used for aircraft applications. The relevant properties of this alloy are given in Table 1. The chemical composition of the rivet material is shown in Table 2. This unalloyed titanium is typically used in non-structural aircraft parts and for engineering applications requiring corrosion resistance [29].

3.2. Joining procedure

The joining equipment used for sample manufacturing is a high-speed friction welding system (RSM 400, Harms & Wende