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Hybrid welding of carbon-fiber reinforced epoxy based composites

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ABSTRACT

The approach for joining thermosetting matrix composites (TSCs) proposed in this study is based on the use of a low melting co-cured thermoplastic film, added as a last ply in the stacking sequence of the composite laminate. During curing, the thermoplastic film partially penetrates in the first layer of the thermosetting composite, leading to macro-mechanical interlocking as the main connection mechanism between the thermoplastic film and the underlying composite. After curing, the thermosetting composite joints with the thermoplastic modified surface can be assembled by welding. Welding of the TSC-TSC joints is performed by ultrasonic and induction welding. The weld strength is investigated by morphological characterization of cross sections and failure surfaces and by mechanical testing. The effect of the thermoplastic film thickness on the welding process and on its outcome is also analyzed. Both induction and ultrasonic welding mostly result in good-quality welded joints. The welding process used as well as the initial thickness of the thermoplastic film are found to have a significant effect on the final thickness of the weld line and on the location of failure. Thicker thermoplastic films are found to ease the welding processes.

1. Introduction

The competitive advantage of thermosetting matrix composites (TSCs) is offset by the associated assembly costs, which, in the case of aeronautic structures, still roughly represent 50% of the manufacturing costs [1–3]. Usually, joining of TSCs has been limited to mechanical fastening and adhesive bonding, sometimes a combination of the two. The diffusion of multi-material design requires the development of novel joining techniques able to overcome the drawbacks of mechanical fastening or adhesive bonding [4]. The major drawback of mechanical fastening is the drilling of holes which result in stress concentrations and weakening of the thin composite structure. To reduce the stress concentrations, the number of plies and, thus, the weight of the component is (locally) increased, significantly reducing the lightweight potential of the composite structure. In addition, mechanical fastening is expensive, generally requiring several working hours on drilling equipment, and it adds the extra weight of the fasteners to the composite structure. Adhesive bonding, although not requiring holes, needs both a rigorous surface preparation, high curing temperatures and pressures and long curing times, which are associated to a significant cost increase [5]. Moreover, some factors during manufacturing of structural bonded joints, such as surface treatments, curing cycle of the adhesive or entrapped moisture in the adherends, can strongly affect the long-term durability of bonded composite joints [1,6].

Lastly, fusion bonding, or welding, is a highly efficient process for joining fiber reinforced thermoplastic composites (TPC), being capable of producing joints in relative short cycle times, which are characterized by equivalent or better performance than adhesively bonded or mechanically fastened joints [7]. Fusion bonding is based on the melting or softening ability of a thermoplastic polymer with increasing temperature. The associated increase of the mobility of molecular chains enables interdiffusion of the thermoplastic molecular chains of the joint adherends across the joining interface [7]. Several fusion-bonding techniques are available for joining thermoplastic matrix composites, which are based on different heating mechanisms, such as hot plates, hot gas, ultrasonic, microwaves, laser, induction and friction stir [8–11]. Fusion bonding is in principle not possible for TSCs since they cannot melt or soften owing to their crosslinked molecular structure. For this reason, the welding of thermosetting composite structures has been scarcely considered in the literature.

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In order to enable the use of welding for the joining of thermoset composite structures, Don et al. [12] patented a method for resistance welding of TPCs to cured TSCs based on the co-curing of a thin thermoplastic film of Polyethersulfone (PES) on the thermosetting composite stack. Co-curing of a thermoplastic film, hereafter referred to as "coupling film", with TSCs has been used or suggested for welding of TPCs to TSCs with various coupling layer materials such as Polysulfone (PSU) [13], Polyphenylenesulfide (PPS) [14], Polystyrene (PS), Polyether ether ketone (PEEK) [15] and Polyetherimide (PEI) [16]. In the case of TSC-TSC welded joints, the very scarce information available in the open literature indicates the use of Polyvinylidene fluoride (PVDF) as preferred coupling layer material [5,17]. Recently, some of the authors of the present paper have used Polyamide 6 (PA6) coupling layers to achieve hybrid joining of aluminum to TSC sheets through ultrasonic metal welding [18].

The selection of the coupling layer material is constrained by various requirements such as processing temperature, high adhesion to the TSC adherend and mechanical and environmental performance of the resulting welded joint. The processing temperature of the coupling layer, i.e. the temperature range at which it can be welded, plays, together with the heating time in the welding process, a crucial role in the potential thermal degradation of the TSC adherend during welding. Coupling layer materials with welding temperatures lower or similar to the glass transition temperature of the thermosetting resin, such as PVDF, are preferred to minimize the risk of thermal degradation [5,17]. Coupling layers with higher welding temperatures can as well be used but require additional strategies to prevent thermal degradation and/or deconsolidation, such as an increasing the thickness of the coupling layer [16] or significantly reducing the heating times [15]. Adhesion of the coupling layer material with the TSC adherend affects how strong and durable the connection between the two elements is. A potentially strong and durable connection between the thermoplastic coupling layer and the TSC adherend can be achieved through diffusion of the epoxy monomers into the thermoplastic film during the co-curing process. This will cause local swelling and dissolution of the thermoplastic resulting in an gradient interphase, typically between tenths and hundreds of microns thick, between the pure epoxy and the pure thermoplastic [19,20]. According to some authors, this process might as well lead to semi-interpenetration of the polymer networks [7]. Nevertheless, the formation of TP-TS gradient interphases and/or semi-interpenetrating networks poses restrictions to the nature of the TP coupling layer material, chiefly related to its solubility in the selected epoxy system. Typically, amorphous thermoplastic polymers, such as polyetherimide (PEI) or polyphenylene ether (PPE), are known to create gradient interphases with some commercial epoxy systems [19]. Amorphous thermoplastic polymers are however known to have low chemical resistance. Alternatively, in the cases where no solubility exists between the coupling layer material and the thermosetting resin in the TSC adherend, connection between the two elements can still be created through macro-mechanical interlocking and/or chemical adhesion. To the end of achieving macro-mechanical interlocking, Jacaruso et al. [21] proposed the use of coupling layers consisting of fabric layers partially impregnated with TP resin. Macro-mechanical interlocking between the coupling layer and the TSC was achieved through flow of the TS resin into the dry fabric areas during the co-curing process. Alternatively, Grefe et al. [22] proposed the use of laser ablation to create texture features on the already cured TSC adherend which led to macro-mechanical interlocking upon melting and flow of the TP resin into the texture features during the welding process. It should be noted that in this last case no coupling layer was used on the TSC adherend. Finally, attaining chemical adhesion between the thermoplastic coupling layer and the thermosetting resin is a challenging task owing to the chemical inertness of thermoplastic resins. Nevertheless, some promising results have been obtained through UV-O_3 treatment of the TP coupling layer prior to the co-curing process [15].

In this paper, for the first time, a preliminary feasibility study on induction and ultrasonic welding of thermosetting matrix composites, co-cured with a top thermoplastic layer, is presented. Even if the approach of co-curing a thermoplastic film is known for the welding of thermosetting composites, its application to ultrasonic welding and induction welding of thermosetting composites is not present in the literature to the best of our knowledge.

Aiming at widening the currently scarce knowledge on the topic, this paper focused on welding of TSC adherends through a novel low-melting thermoplastic coupling layer. The TSC was carbon fiber reinforced epoxy with 180 °C curing temperature and the coupling layer material was Polyvynilbutyral (PVB), which is a semi-crystalline thermoplastic polymer with melting temperature in the 150—170 °C range. PVB is a low-cost polymer characterized by excellent binding and film forming ability and adhesion to many surfaces [23]. It has usually been used as an interlayer material in the manufacture of laminated glass for its high mechanical strength and optical clarity [24] but never as a coupling layer for welding of TSCs. A remarkable feature of the PVB coupling layer is that, owing to its low viscosity during the first stage of the co-curing process, i.e. before gelation of the epoxy resin, the PVB resin was able to partially penetrate in the first layer of the carbon-epoxy composite. This resulted in an alternative procedure to generate macro-mechanical interlocking between the coupling layer and the underlying composite. The CF/epoxy adherends with the PVB coupling layer were subsequently welded and their strength and failure mechanisms were analyzed. Two welding techniques novel for the intended application, namely induction and ultrasonic welding, and two different coupling-layer thicknesses were comparatively evaluated.

2. Experimental

A carbon fabric/epoxy prepreg supplied by Hexcel 3501-6 with a fiber volume content of 58% was used. 14 plies of CF/epoxy prepreg were stacked adding as a last ply a poly-vynil-butyral (PVB) film (Mowital, supplied by Kurakay) with two different thicknesses (75 and 250 μm). PVB is a random terpolymer containing butyral and hydroxyl side groups with a small amount of acetate units [25]. The hydrophobic vinyl butyral units provide elasticity and toughness while the hydrophilic vinyl alcohol units confer high adhesion to inorganic materials [26]. PVB has a glass transition temperature between 60 °C and 85 °C and a melting range between 150 °C and 170 °C.

The CF/epoxy/PVB stacks were cured in a hot platen press at 180 °C and 2 bar for 1 h with no vacuum bag, resulting in laminates with a final thickness of 2.7 mm. Subsequently, the CF/epoxy/PVB cured adherends (cut from the CF/epoxy/PVB laminates) were welded in a single lap configuration as schematically shown in Fig. 1. Two welding processes, namely induction and ultrasonic welding, were applied to join two adherends with a 250 μm-thick coupling layer (referred to as Ind250 and Us250 joints, respectively) and two adherends with a 75 μm-thick coupling layer (referred to as Ind75 and Us75 joints, respectively).

An induction welding setup (Fig. 2a), operating at 600 kHz and 220 V, tuning the power between 1 and 2 kW and using a coil speed of 2 mm/s, was used [27]. Heating was produced within the conductive patterns present in the carbon fiber fabric without adding any additional conductive mesh at the welding interface. The feedback control on the electric current flowing in the coil was based on a surface temperature measurement through an