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Joining of thermoplastic structures by Friction Riveting: A mechanical and a microstructural investigation on pure and glass reinforced polyamide sheets

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ABSTRACT

Friction Riveting is a spot joining, which consists in rotating a cylindrical rivet and inserting it into clamped sheets. In the first friction phase, the rotational speed and the applied axial force heat the material by friction plasticizing it. After that, the spindle rotation is stopped and the axial force is increased passing to the so called forging phase. Several working parameters, such as the rotational speed, the friction and forging times, and the friction and forging pressure, have to be optimized to achieve sound connections.

In the proposed work, the attention was given to the joints of sheets made of a thermoplastic material with and without short glass fiber reinforcements. Rivets were made of Titanium Grade 2. The quality of the obtained results was verified by tensile tests. Moreover, microscopic observations were performed analyzing the material deformation and integrity inside the connection volume. The influences of the monitored process parameters on the above highlighted outputs were reported providing a guideline for the process execution.

1. Introduction

In the recent years, various industrial sectors, such as automotive, aeronautic and power generation fields, have increased the use of multi-materials and hybrid components under the influence of green policies and innovative manufacturing technologies. The quality of the produced components is closely linked to the connection of the parts. Briefly, joining is a complex process, which allows single parts to be assembled all together achieving specific performances in mechanical, physical and chemical terms.

The complexity of products demands for new functional processes, even if just metals have to be connected. In 2013, Mori et al. [1] focused their study on joining by plastic deformation, highlighting that there are significant variants able to improve accuracy, reliability and environmental safety of joined parts as well as to generate opportunities to design new products made of dissimilar materials.

The joining difficulties increase if materials of different classes have to be combined adequately. For example, the limited joining capacity or the easy failure of joined polymers and metals are due to their physical and chemical dissimilarity [2]. However, the combination of dissimilar parts can be guaranteed using different joining techniques. Martinsen et al. [3] summarized the state of the art in joining dissimilar materials classifying them in mechanical, chemical, thermal and hybrid processes. They highlighted the vastness of the topic and, therefore, described methods useful to the process selection. Haddadi and Abu-Farha [4], in 2015, stated that reaction at the interface and material incompatibilities are the most challenging barriers in joining dissimilar materials.

Welding [5,6], adhesive bonding [7] and mechanical fastening (MF) techniques need different approaches if they have to be applied to pure polymer or polymer matrix composites (PMC) instead of just metals. Among the variety of welding techniques, one of the most promising for the joining of hybrid structures is ultrasonic welding, where parts to be joined are held together under pressure and subjected to ultrasonic vibrations.

Various solutions belong to the MF process category, such as bolted joints, riveting and clinching. The use of rivets or bolts has been widely analyzed to join laminates [8]. Modified self-piercing rivet (SPR) allows the joining of the sheets minimizing delamination at the points of piercing [9]. Numerical models have been developed to predict failure load and failure modes of mechanically fastened composite joints giving mathematical tools to judge the various solutions [10]. In 2017, Lambiase and Ko [11] investigated two-steps clinching, where a reshaping deformation is used at the end of the clinching phase to improve the mechanical behavior of the connections.

The continuous research of improving the joining quality has

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pushed the research to combine various techniques [12,13].

Nevertheless wide joining solutions, new designs and materials [14] have been pushed to new techniques, such as Injection Clinching Joining [15], Friction Lap Joining [16] and Friction Spot Joining [17]. Friction Riveting (FricRiveting), patented by Amancio Filho [18], is one of a these emerging solutions. This technique uses a cylindrical metallic rivet to connect thermoplastic-metal parts plasticizing and deforming the tip of the rotating rivet heated by frictional forces. Before the joining phase starts, a specific equipment clamps the sheet to be connected, firmly. The process, performed by a high-speed friction welding system, is divided in two different phases. During the first one, known as heating phase, the metallic rivet, rotating, gets into the components to be joined. At the end of this phase, the spindle stops and the rivet is pushed into the sheets to be connected. This is called forging phase. The FricRiveting temperatures are usually found to lie within the early stage of degradation of the investigated thermoplastics [19]. Different variables, such as the rotational spindle speed, the friction time and the friction pressure, the forging time and the forging pressure, have to be combined to optimize the quality of the connection. A better understanding of the mechanical behavior of the joint can be reached by numerical analyses, which are quite complex to perform taking into account the metal-plastic interaction [20].

The feasibility of Friction Riveting on thermoplastic composites has been proved considering plastic matrixes reinforced with short fiber [21] and laminates [22]. High-performance plastics, i.e. Polyetherimide (PEI) and poly-ether-ether-ketone (PEEK) [20–23] have been usually investigated, while just a research has been focused on polycarbonate [24], which belongs to engineering plastics generally characterized by lower mechanical properties. This is relevant to the FricRiveting dynamics being the rivet tip deformed by a right combination of temperature and plastic resistance during the forging phase.

In the work here proposed, FricRiveting was used to join an engineering plastic, polyamide 6 with and without glass fiber (GF) reinforcement. The feasibility of the process was proved using a customized equipment installed on a traditional milling machine and the influence of various process parameters on the quality of the connection was investigated.

Tensile tests were performed to judge the anchoring of the rivet with the sheet. Furthermore, preliminary analyses were carried out to evaluate the influence of the process parameters on the strain distribution of the worked polymer around the joining area. These tests used an Electronic Speckle Pattern Interferometry (ESPI) or rather an interferometric non-destructive testing technique that works in full-field modality [25,26]. Finally, optical observations have been performed to judge the integrity of the material in the same area.

2. Materials, equipment and methods

2.1. Materials

Polyamide 6 (PA6) is an engineering thermoplastic used in several sectors going from construction to lighting, from automotive to aviation industries [27,28]. It is characterized by mechanical properties allowing light components to be designed and manufactured, for instance, for the transport sector, where the weight reduction is one of the main priority [29]. Specifically, raw plastic materials were commercial grades supplied by Lanxess (Cologne, Germany) under the trade names Durethan B30S and Durethan BKV30H. The former is a white virgin grade PA6 resin while the latter is a black grade containing 30 wt% of glass fibers and a low content of carbon black usually included in formulations for the automotive field just for aesthetic reasons.

Holed cylindrical rivets, with an external diameter of 5 mm and a thickness of 1 mm, were made of titanium grade 2. Their length, equal to 60 mm, was oversized to allow the tensile tests, which were carried out to quantify the joint strength.

Table 1 reports the main mechanical and thermal properties of the materials used in the performed research. These values are provided by the producers.

2.2. Sheet preparation

The sheets to be joined were obtained by compression molding. PA6 based resins, dried at 80 °C for 3 h, were molded in 5 mm thick sheets under the temperature and pressure profiles shown in the following Fig. 1.

2.3. Equipment

The feasibility of FricRiveting was proved without using a dedicate friction welding system [17–24]. Specifically, a milling machine was utilized to carry out the planned experiments. Changing the process parameters, the rivet stroke becomes a variable that has to be controlled and the loads during the process become the outputs to measure. The required high spindle speeds necessary to perform the process, up to 40,000 rpm, were reached by a speed multiplier, which was placed inside the spindle of the milling machine. The spindle speed is properly increased to get a desired temperature increment during the heating phase.

Two 5 mm thick sheets, blocked to each other by a suitable equipment, were joined. The equipment was placed on a dynamometer to monitor the loads and a thermocouple and a thermo-camera were utilized to check the temperatures during the process. The thermocouple was embedded in a pre-defined position chosen taking into account the experimental evidences, highlighted in [18], where it was noticed how the temperature trend, locally measured, presented consistent differences according to the position of the thermocouple along the specimen thickness (z-axis). The upper side of the lower sheet was the selected position to embed the thermocouple with the depth of the hole that was fixed with a distance of around 1 mm between the tip of the measuring tool and the external surface of the rivet. The experimental equipment is reported in Fig. 2 while a sketch of the performed process and a deformed rivet after the tensile test are shown in Fig. 3.

2.4. Monitored outputs and investigated process variables

The process dynamics are well understood. The first phase of the process has to generate a specific amount of heat around the tip of the rivet in a defined time. This heat has to increase the ductility of the metallic rivet, which is forged during the second process phase. The wanted deformation can be reached pushing the rivet against a material, pure or reinforced thermoplastic, which being further from the heated zone and, taking into account the low conductivity of the polymers, is at a lower temperature and with more elevated mechanical properties. A compromise between reached temperature (and its associated effects on the thermoplastic rheology that determines the resistance to the rivet penetration) and forging force needs to be found for each combination of rivet and sheets. For this reason, recorded temperature and forging force were the outputs quantitatively measurable that, together with the maximum strength required to pull out the rivet from the sheets, were used in a proposed mathematical procedure to identify the optimal combination of process parameters.

Specifically, the maximum pulling strength was measured by an Instron testing machine with a traverse speed of 1 mm/min at room temperature and with a load cell of 5 kN. The connected parts were tested fixing them in a sample holder made of two bolt-connected rigid plates, while the rivet is clamped to the moving traverse and pulled out from the sheets (Fig. 4). Due to the complex geometry of the deformed rivet, the determination of a real cross-sectional rivet area was very difficult and the joint strength was presented only in terms of tensile force.

The ESPI technique was, instead, used to qualitatively investigate the out of plane displacements of stressed specimens enabling the