FRICTION RIVETED HYBRID JOINTS OF SHORT-GLASS-FIBER-REINFORCED POLYAMIDE 6 AND 6056-T6 ALUMINUM ALLOY

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Abstract – Hybrid joints of short-glass-fiber-reinforced polyamide 6 and 6056-T6 aluminum alloy were produced by friction riveting under different processing conditions. The effects on the rivet anchoring efficiency and mechanical performance of the joints as well as the microstructural changes of the polymer composite were evaluated. The increase in the values of both rotational speed and joining force led to increased heat input, which provided joints with greater rivet anchoring efficiency and thus higher tensile strength. In the thermo-mechanically affected zone of the composite glass fiber breakage and polyamide chain scission were observed; however, their impacts on the quasi-static mechanical performance of the joints are negligible.

Keywords: joining; welding; hybrid structures.

Introduction

The use of polymer composites in polymer-metal hybrid structures to replace all-metal parts has been grown considerably in the automotive industry. This is no doubt the best way to help meet emerging fuel-economy regulations of this sector [1].

Friction riveting, a polymer-metal joining technique based on mechanical fastening and friction welding, has been proven to work with various combinations of materials [2-7]. In the basic configuration – i.e., the metallic-insert joint geometry – a rotating cylindrical metallic rivet is pressed into a polymeric plate producing frictional heat that allows the rivet to be plastic deformed and anchored inside the polymeric plate (Fig. 1).

Figure 1 - Steps of the Friction Riveting process in metallic-insert joints. (a) Positioning of the joining parts; (b) insertion of the rotating metallic rivet into the polymeric plates (frictional phase); (c) plastic deformation of the rivet tip by increasing the axial force (forging phase); (d) joint consolidation.
Two main process-related affected microstructural zones are created in the polymer part. The polymer thermo-mechanically affected zone (PTMAZ) is a thin layer around the metallic rivet produced by solidification of a small amount of polymer that had been softened/melted as a result of the thermo-mechanical work generated by the friction riveting. The polymer heat affected zone (PHAZ) is a region in between the PTMAZ and the base material produced by cooling of a given amount of polymer that had been heated up but not softened during the process.

The aim of this study was to evaluate the relationships between the processing parameters, rivet anchoring efficient, tensile strength and thermo-mechanical changes of the polymer composite in short-glass-fiber-reinforced polyamide 6 and 6056-T6 aluminum alloy friction riveted joints.

**Experimental**

The polymeric composite part was a 10.8 mm thick extruded sheet of polyamide 6 reinforced with 30 wt% short glass fibers. The metallic part was an aluminum alloy 6056-T6 in the form of cylindrical rivets of 4 mm in diameter and 50 mm long.

The joints were produced in a friction welding machine (RSM410, Harms & Wende, Germany). The processing conditions along with the maximum temperatures reached during the process (measured using an infrared thermo-camera) are shown in Table 1.

**Table 1 - Friction riveting conditions and maximum process temperatures reached for the PA6-30GF/AA6056-T6 joints investigated in this study**

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The geometrical features of the rivet in the joints were evaluated by optical microscopy (OM) using a Leica DM IRM equipment. The analysis was performed on samples taken from the mid cross-section of the joints, which were prepared according to metallographic standards.

The mechanical strength of the joints was evaluated by the ultimate tensile force displayed in the T-pull tensile testing using a Zwick/Roell equipment with a crosshead speed of 1 mm min⁻¹ at room temperature.

The extent of degradation of the PA6 in the PA6-30GF composite was evaluated by dilute solution viscosity measurements based on the ASTM D2857. Samples taken from the PTMAZ were dissolved in 85% formic acid, filtered through a PTFE membrane (average pore size of 0.2 μm) to separate from the filler (glass fiber and carbon black), and the final concentration of PA6 solutions was adjusted to 0.1 g/dL. Measurements were performed in an Ubbelohde viscosimeter type 1.
immersed in a water bath set at 25 ± 0.1 °C. The intrinsic viscosity values were determined by the single point method of Billmeyer through the Eq. 1, where \([\eta]\) is the intrinsic viscosity, \([\eta_{\text{red}}]\) is the reduced viscosity and \([\eta_{\text{iner}}]\) is the inherent viscosity:

\[
[\eta] = (0.25 \cdot \eta_{\text{red}}) + (0.75 \cdot \eta_{\text{iner}})
\]

(1)

The viscosity average molecular weight \(\langle M_v \rangle\) of the polyamide 6 was calculated by the Mark-Houwink-Sakurada approach (Eq. 2), where \([\eta]\) is the intrinsic viscosity and the constants \(K = 2.26 \times 10^{-4}\) dL/g and \(a = 0.82\):

\[
[\eta] = K \cdot M_v^a
\]

(2)

The level of the glass-fiber breakage in the PA6-30GF composite was evaluated by optical microscopy. The glass fibers were recovered from the PTMAZ through the separation procedure described earlier. The fibers were spread over a glass plate with the aid of a 1:1 solution of distilled water and ethanol and then left to a hot plate until the complete evaporation of the solution. The lengths of the glass fibers were determined using Image J software. Around 1000 fibers were analyzed for each sample and the number average length (\(l_n\)), the weight average length (\(l_w\)) and the polydispersity index (\(P\)) were obtained.

**Results and Discussion**

The mid cross section images of some selected PA6-30GF/AA6056-T6 joints produced in the conditions of low (C3), medium (C9) and high (C13) heat inputs are shown in Fig. 2. From left to the right, the increase in both rotational speed and joining force yield higher heat input and thus higher processing temperatures, which in turn lead to greater plasticized metal volume and thus higher deformation of the rivet tip.

![Figure 2 - Mid cross section images of PA6-30GF/AA6056-T6 friction riveted joints produced under conditions of low ((a) C3), medium ((b) C9) and high ((c) C13) heat inputs](image)

The mechanical strength of joints (Fig. 3) showed a linear increase with the volumetric ratio, a heat-input dependent geometrical parameter which considers the interaction volume of the polymer that is above the tip of the rivet. Joints produced in the conditions C8 and C13 that provided higher heat inputs and thus greater volumetric ratios showed best mechanical strengths, with ductile behavior through the fracture of the metallic rivet outside the composite plate. The other joints presented brittle fracture through rivet pull-out.

Fig. 4 shows the effects of friction riveting on the size of the glass fibers in the PTMAZ of joints prepared under conditions of low (C3), medium (C9) and high (C13) heat inputs. As compared to the PA6-30GF base material, there was a decrease in the average fiber lengths with no change in the polydispersity. Besides, the level of fiber breakage seems not to be dependent on the processing conditions. Despite of the fiber breakage, the \(l_w\) values for the joints produced are a little higher than the critical fiber length for effective reinforcement of the PA6 matrix, which is 167 μm according to estimation made using the Kelly-Tyson model.
Figure 3 – Dependence of ultimate tensile force in T-pull mechanical testing on the volumetric ratio for PA6-30GF/AA6056-T6 friction riveted joints processed under different conditions.

Figure 4 - Histograms of the glass fiber lengths in the PTMAZ of PA6-30GF/AA6056-T6 friction riveted joints processed in the conditions C3, C9 and C13. The value for the unprocessed PA6-30GF base material (BM) is included for comparison.

Fig. 5 shows the effects of the maximum temperature achieved in the joints during processing on the viscosity average molecular weight of PA6 samples extracted from PTMAZ. The value for the base material is included for comparison. The increase in the process temperature due to increasing rotational speed and joining force leads to decrease of molecular weight of PA6, as result of thermo-mechanical degradation by chain scission. There is a linear correlation between these two data sets. The reduction in the molecular weight was in the range of 6% to 19%, respectively, for the friction riveting conditions that yield lower (C3) and higher (C13) heat inputs.
Figure 5 – Dependence of viscosity average molecular weight of PA6 in the PTMAZ on the process temperature for PA6-30GF/AA6056-T6 friction riveted joints. The value for the unprocessed PA6 base material is included for comparison.

Conclusions

Friction riveted hybrid joints of short-glass-fiber-reinforced polyamide 6 and 6056-T6 aluminum alloy with great anchoring efficient and thus outstanding mechanical strength were produced. This has been achieved by means of the increase in the process temperature following an increase in both rotation speed and joining force. On the other hand, this is accompanied by the glass fiber breakage and degradation of PA6 chains in the thermo-mechanically affected zone of the polymer composite (PTMAZ), without undermining the quai-static mechanical strength of the joints. This is mainly due to the fact that in this test the load is sustained by a much larger volume of composite than that of PTMAZ, which is in turn unaffected by the friction riveting.

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References