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Effect of temperature on fatigue strength of vibration welded and unwelded glass reinforced nylon 6

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ABSTRACT

The effect of temperature on the tensile and fatigue strength of vibration welded and unwelded 30 wt% glass fiber reinforced nylon 6 (PA6GF) was experimentally examined. Fatigue tests were performed under sinusoidal constant amplitude tension–tension load at a stress ratio of $R = 0.1$ and within the frequency range of 2–10 Hz. Stress levels from just under the tensile strength down to the run-out point, at 5 million cycles, were used. It was found that increasing temperature led to a significant decrease in both tensile strength and fatigue life. However, it was also noted that for both welded and unwelded PA6GF, the endurance ratio, i.e., the ratio of fatigue strength to static tensile strength, was approximately 45% regardless of the temperature. The fatigue notch factor (K_f) lies between 1.5 and 1.75 regardless of test temperature.

1. Introduction

Nylons have been the material of choice for vibration welded under-hood automotive parts such as air intake manifolds (AIM) for over a decade [1]. The service conditions for such applications can be harsh, with temperature extremes from −40 to 130 °C, which is why nylon and its composites have become commonly used materials within the automotive industry [1]. The vibration welding (VW) process offers advantages over other joining processes due to its short manufacturing cycle times, relatively simple equipment requirements, no pre-welding surface preparation and low risk of material deterioration due to overheating at the interface [2]. Previous studies have demonstrated that the vibration welding process parameters such as welding frequency and amplitude, weld penetration and weld pressure can affect weld strength [3–8]. Under optimal conditions, the static vibration welding strength of unreinforced nylons can approach that of the unwelded nylon; however for glass fiber reinforced nylons, the static vibration welding strength can only match that of the unreinforced unwelded nylon, because little glass fiber reinforcement occurs at the weld, due to poor fiber orientation [5,9].

Since nylon materials are used increasingly in applications where they bear considerable stress under cyclic loads, the fatigue properties of vibration welded nylon materials have been investigated [10–12]. Tsang et al. [10,11] studied the fatigue behavior of vibration welded nylon 6, nylon 66, as well as their 30 wt% glass fiber reinforced composites, under sinusoidal tension–tension load at a loading ratio (R) of 0.1. They studied the effect of a high, 4 MPa, and a low, 0.8 MPa, welding pressure on the static and fatigue strength of vibration welded specimens at room temperature. Regardless of the matrix material and reinforcement, the fatigue behavior of these nylon composites was similar, with a slight improvement of fatigue life when a low welding pressure of 0.8 MPa was applied. For the vibration welded nylon materials studied, the fatigue limit in terms of maximum stress at $R = 0.1$ was reported to be 0.33 of the tensile strength. Glass fiber reinforcement did not improve the fatigue behavior over unreinforced nylon, because the glass fibers were oriented parallel to the weld plane after vibration welding. The effect of inherent anisotropy of the material caused by flow-induced orientation of fibers was also reported by Zhou and Mallick [13] for nylon 66 reinforced with 33 wt% short glass fiber. They found that the fatigue strength of the material was significantly higher in the flow direction than in the transverse direction. Hartmann et al. [14] showed that fatigue results obtained from simple geometry specimens are transferrable in the design of more complex components. They determined the fatigue life of flat specimens made of short glass fibre reinforced polyamide 6,6 under both constant and variable amplitude

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loadings. It was verified that fatigue life behavior observed from the flat specimens could be transferred to the component related specimen by conducting finite element calculation and internal pressure fatigue tests on the component related specimens.

Less attention has been directed towards the fatigue performance of nylon materials at elevated temperatures. Jia and Kagan [15] conducted tension–tension fatigue tests on glass fiber reinforced nylons, at various test temperatures ranging from −40 to 121 °C, and observed that fatigue strength decreased monotonically with increasing test temperature. They showed that at room temperature (23 °C) nylon 66 had slightly higher fatigue strength than nylon 6, but the trend was reversed at lower and higher temperatures. A previous study by Hahn et al. [16] has shown that the fatigue crack propagation rate in nylon 66 reached a minimum at 0 °C and then increased with either increasing or decreasing temperature, corresponding to an optimum combination of storage modulus so as to minimize fatigue damage and loss compliance values that maximize dissipation. However, Hahn et al. [16] studied temperatures up to only 50 °C.

Since complex nylon components are often welded and required to serve at elevated temperatures, the impact of vibration welding on material properties at elevated temperatures cannot be overlooked. This study experimentally examines the effect of temperature on the tensile and fatigue properties of vibration welded 30 wt% glass fiber reinforced nylon 6, the latter obtained under sinusoidal tension–tension loading at a loading ratio of $R = 0.1$. Non-welded material data are also included for reference. The results are analyzed using stress-life (S–N) curves, and the fatigue notch factors at various test temperatures for VW specimens are evaluated as a guideline for designing purposes.

2. Experimental procedures

A 30 wt% short glass fiber reinforced nylon 6 (PA6GF, glass content determined by burning off the organic phase and fillers in a furnace at 900 °C in air) was used for this research. The PA6GF was provided in the form of pellets, which were dried at 80°C for 24 h prior to injection molding into plaques using an Engel 55 ton injection molding machine. The molded plaque dimensions were 100 mm × 100 mm × 3.2 mm.

The orientation of the glass fibers in the molded plaque can have a significant impact on its mechanical properties. The orientation of the fibers is affected by the flow of the material in the injection molding process [9,17,18]. Generally, in thin edge-gated plaques during cavity filling, the preferential fiber orientation is parallel to the melt flow direction as shown in Fig. 1 [19].

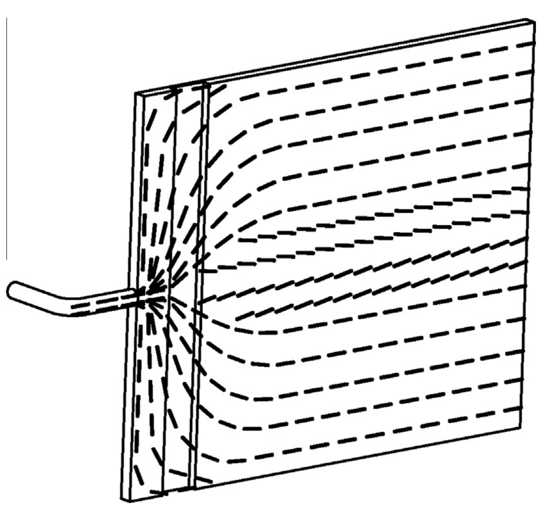

Fig. 1. Flow direction and predominant glass fiber orientation for a plaque [11].

The plaques were cut and the edges were milled to create flat plates with the dimensions of 60 mm × 100 mm × 3.2 mm in preparation for manufacturing butt welds via vibration welding. The cuts were made parallel to the flow direction (Fig. 2) [11] so that, as is generally found in industry, the fibers are preferentially aligned along the length of the plate. Two 100 mm × 60 mm plates were welded together at the milled edges to form one weldment approximately 100 mm × 120 mm.

The method used to manufacture vibration welded specimens was duplicated from Tsang et al. [10,11]. In the present study, a low welding pressure of 1 MPa was applied. The top plate was oscillated by a spring-mass system vibrating at 212 Hz, with peak-to-peak amplitude of 1.8 mm, while the bottom plate was held in place. The weld penetration was 1.5 mm which, once reached, the vibration was ended and the weld was allowed to solidify under constant welding pressure.

The welded plates were then machined into dog bone specimens with the dimensions shown in Fig. 3, with the loading axis perpendicular to the preferential fiber direction. Unwelded plaques were also machined into dog bone specimens with the same gauge dimensions and the same orientation; they were slightly shorter in overall length.

Since it has been shown that water content can have a significant effect on the properties of nylon 6 [16,20], the nylon specimens were tested dry-as-molded or were dried in an oven at 80 °C for approximately 50 h before testing. The methodology recommended in ASTM D7791 was adapted for the fatigue testing in this work. For the fatigue tests, the specimens were subjected to constant amplitude sinusoidal tension–tension fatigue. The loading ratio, R was 0.1. Specimens that ran for over $5 \cdot (10)^6$ cycles without breaking were considered to be runouts. The highest stress level at which run out was achieved was taken as the fatigue limit; three specimens were typically taken to runout for each condition. The loading frequency for the fatigue tests was kept between 2 and 10 Hz to be consistent with previous studies available in the literature [11,21]. Test frequency was decreased with increasing stress level in order to avoid the excessive hysteretic heating that causes the specimens to fail due to permanent plastic deformation rather than fracture. The loading frequency during each test was kept constant as stipulated in ASTM D7791 – Standard Test Method for Uniaxial Fatigue Properties of Plastics. All fatigue tests were performed within an environmental chamber incorporating a furnace that allowed for the temperature to be controlled within ±2 °C at the gauge section of the specimen. Fig. 4 shows one actual welded fatigue specimen set up in the environmental chamber, the red frame marks the thermocouples used to control and measure the temperature within the chamber.

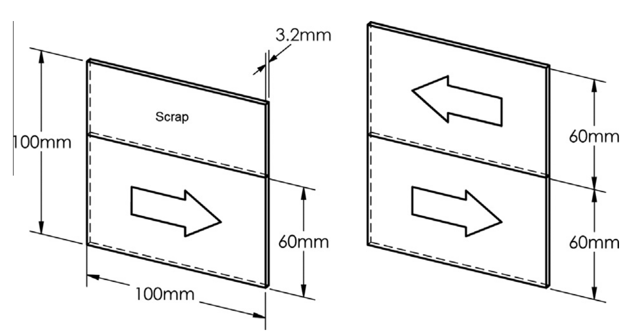

Fig. 2. Pre-welding cut and welding alignment for nylon plaques used in butt welds [11]. The arrows denote the flow direction of the polymer melt during injection molding.