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EFFECTS OF TIME AND TEMPERATURE CONDITIONS ON THE TENSILE-TENSILE FATIGUE BEHAVIOR OF SHORT FIBER REINFORCED POLYAMIDES

Abstract

To support the design of the automotive under-the-hood components against fatigue, we analyzed the performance of the short glass fiber reinforced (33% by weight) polyamides (PA6 and PA66) using short term (tensile strength) and long term (fatigue strength) criteria. Comprehensive fatigue tests were conducted at temperatures from – 40°C to 121°C, using injection molded type I tensile specimens aged for 0, 100, 500 and 1000 hours, at a load frequency $f = 5$ Hz, a stress ratio $R = 0.1$, and in the range of cycles to failure from $2{\cdot}10^3$ to $2{\cdot}10^6$.

Without aging, the highest fatigue strength and fatigue life for both PA6 and PA66 were found at – 40°C; it decreased significantly at 23°C, and decreased further at 121°C. The fatigue strength of PA6 is higher than that of PA66 at – 40°C, but the reverse is seen at 23°C. At 121°C, the fatigue strengths of PA6 and PA66 are virtually the same.

Aging at 121°C improved the tensile strength of polyamides (PA6 and PA66) as aging time increased from 100 to 1000 hours, and this process seemed to be more influential for PA6.

Introduction

Short fiber reinforced polyamide thermoplastics have important applications in the automotive under-the-hood, cyclically loaded components where the materials must endure continuously a severe environment combined with high temperature, cyclic stress / strain, and corrosive fluids and gases[1]. The design and performance of the highly stressed thermoplastic components depend heavily on our understanding of the materials' long-term mechanical properties, especially their fatigue and creep behaviors[2-5].

Analysis of fatigue behavior on the reinforced thermoplastics has been conducted in the past at room temperature, mostly on short carbon and glass fiber reinforced materials including PA66, polycarbonate, polysulfone, polyphenylene sulfide[3,4]. It was found[4] that, for fatigue life up to 10^6 cycles, glass fiber (40%) reinforced PA66 exhibited higher fatigue resistance than polycarbonate reinforced by the same amount of glass fibers (Figure 1).

The current study summarizes our investigation on the tensile-tensile fatigue behavior of short glass fiber reinforced PA6 and PA66 thermoplastics. Fatigue test and analysis were performed at three temperatures which components made of these materials are most likely to experience during their life time: – 40°C, 23°C and 121°C. Aging of PA6 and PA66 was performed at 121°C for 100, 500, and 1,000 hours and its effect on the fatigue behavior was analyzed. Included also in the investigation is the static tensile strengths of the selected materials and their correlation to the corresponding fatigue behaviors.

Materials and Experimental Procedures

The thermoplastics used in this investigation were heat stabilized PA6 and PA66. They were both reinforced by 33wt.% of short glass fibers, and contained black pigment typical for the under-the-hood components.

Samples for tensile strength and tensile-tensile fatigue tests were injection molded into type I tensile specimens, according to ASTM D638-93[6].

Aging of the materials was conducted by placing dry-as-molded (DAM) specimens into a chamber preheated and maintained at 121 ± 1°C. The times of aging were 100, 500, and 1000 hours. Both DAM and aged specimens were sealed tightly prior to testing in order to minimize their exposure to moisture.

The static tensile strength tests were conducted using Instron 4505 with an environmental test chamber, at a crosshead speed of 5mm/min and temperatures of – 40, 23, and 121°C (± 1°C). Cooling and heating in the chamber was provided using liquid nitrogen and electrical heating, respectively.

The tensile-tensile fatigue tests were conducted using Instron 1331 servohydraulic test system, equipped by an environmental test chamber similar to the one used in the strength tests. Tests were conducted under the load control mode, where the system generated a sinusoidal loading function at a frequency of 5 Hz. The cyclic stress ratio, R = (min. stress) / (max. stress) = S_{min}/S_{max}, was maintained at 0.1 throughout the experiments. Specimens were tested at – 40, 23, and 121°C. As in the static tensile strength tests, an environmental chamber was used for testing at – 40 and 121°C (± 1°C).

Results and Discussions

Tensile Strength of PA6 and PA66

The tensile strengths of PA6 and PA66 were found to decrease continuously as the temperature increased from – 40 to 23°C, and from 23 to 121°C. Comparing the two materials, PA6 was found to have out performed PA66 at – 40°C, where its tensile strength is higher than that of PA66 (both without aging). At room temperature (23°C), the tensile strengths of these two materials are virtually the same; and at 121°C, the strength of PA66 becomes higher than that of PA6.

Aging, on the hand, has resulted in an increase in the tensile strengths for PA6 and 66 (see Figure 2). For PA6, the tensile strength at room temperature (23°C) increased by about 3% after aging for 500 hours, and 4% after aging for 1,000 hours; for PA66, the room temperature tensile strength increased about 1% after 1,000 hours of aging. The increase in tensile strength is more significant at 121°C for both materials, where an 11% and 14% increase were found for PA6 after aging for 500 and 1,000 hours, respectively; and a 5% increase was found for PA66 after aging for 500 hours.

Tensile-Tensile Fatigue Behavior of PA6 and PA66

Shown in Figures 3 and 4 are the fatigue strength (defined by the stress amplitude, $S_a = (S_{max} - S_{min})/2$) vs. the cycle to failure, N, for the DAM PA6 and 66 materials (S–N curves). Reflected also on these curves is the influence of temperature on the tensile-tensile fatigue behavior. The tensile-tensile fatigue tests were also conduced for PA6 and 66 aged up to 1,000 hours, and the results are shown in Figures 5 and 6.

For both PA6 and 66, the highest fatigue strength at a given fatigue life was found at – 40°C. It decreased as the temperature increased to 23°C, and decreased further at 121°C, as shown in Figures 3 and 4.

The comparison between the fatigue behaviors of the DAM PA6 and 66 revealed a similar trend found in their static tensile strength. At – 40°C, the fatigue strength of PA6 is higher than that of PA66 within the range of fatigue life in the experiments (2,000 ~ 2,000,000 cycles). This trend is reversed at 23°C where the fatigue strength of PA66 is higher than that of PA6 at the same fatigue life. At 121°C, however, the fatigue strengths between the two materials are virtually the same.

Aging for up to 1,000 hours was found to have resulted in a slight increase in the fatigue strengths of PA6 and 66 at 23°C, but this increase is less significant or consistent, as shown in Figures 5 and 6. At 121°C, aging has caused virtually no change in the fatigue behavior in terms of fatigue strength or fatigue life, for either PA6 or 66.

Fatigue Behavior Analysis

For polyamides, the fatigue strength and the fatigue life was found to satisfy the following empirical relationship[5]

$$S_a = B - m \cdot \log N \qquad (1)$$

where m and B are material constants. The numerical values for m and B are given in Table 1.

The similar study of this relationship was found in the literature[4], where B had been found to equal the static tensile strength of the material. Data from our experiments indicated that the value of B is actually lower than the static tensile strength obtained for the same material at the same temperature. This result implies that, although equation (1) describes very well the relationship between the fatigue strength and its corresponding life time from a few thousand to more than a million cycles, it fails to extrapolate linearly into the low cycle fatigue region where the considerable plastic deformation might have resulted in a failure mechanism different from the one that can be related to equation (1).

Despite the failure of equation (1) in extending to the static tensile strength, the correlation between the fatigue strength and the tensile strength nonetheless was found to exist, as shown in Figure 7. In this figure, the normalized fatigue strength, defined as the ratio of fatigue strength S_a (amplitude) and the tensile strength σ_U, is plotted against the cycle to failure N for PA6 and PA66 aged at different hours and tested at different temperatures. In most cases, it is seen that the plots of normalized fatigue strength vs. the cycle to failure fall into a narrow band, suggesting the existence of a master curve that are characteristic of all materials. Using equation (1), the master curve can be expressed as

$$\frac{S_a}{\sigma_U} = B' - m' \cdot \log N \qquad (2)$$

where B' and m' are material parameters.

Conclusions

(1) Without aging, PA6 was found to have out performed PA66 at – 40°C with a higher static tensile strength. At the room temperature (23°C), the tensile strengths of the two thermoplastics are virtually the same, and at 121°C, the tensile strength of PA66 is slightly higher than that of PA6.

(2) At the two critical temperatures (– 40 and 121°C) for the under-the-hood components, DAM PA6 was found to perform equally well or better than DAM PA66 in terms of the tensile-tensile fatigue strength. At – 40°C, a typical temperature under the severe winter conditions, the fatigue strength of PA6 is higher than that of PA66. At 121°C, a typical working temperature for the under-the hood components, the fatigue strengths of PA6 and 66 are virtually the same.

(3) Analysis at 23°C indicated that the static tensile strength and tensile-tensile fatigue strengths of both materials have increased slightly as a result of aging, and more increase is found in PA6. At 121°C, however, the effect of aging on the fatigue behavior becomes insignificant for both PA6 and 66.

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Key Words

Polyamide, fatigue strength, fatigue life, tensile strength, aging, temperature.

Table 1. Material Parameters for the Tensile-Tensile Fatigue of Short Glass Fiber Reinforced PA6 and PA66 Thermoplastics

Materials / Conditioning		– 40°C (MPa)	23°C (MPa)	121°C (MPa)
PA6				
not aged,	*m*	13.0	4.85	1.64
	B	127.6	70.6	32.0
121°C/100 hr,	*m*	—	4.85	2.46
	B	—	65.9	34.7
121°C/500 hr,	*m*	—	5.25	2.73
	B	—	67.8	37.2
121°C/1000 hr,	*m*	—	3.19	2.53
	B	—	58.1	35.6
PA66				
not aged,	*m*	9.30	4.60	3.43
	B	103.8	66.7	42.4
121°C/100 hr,	*m*	—	3.32	3.00
	B	—	61.9	40.3
121°C/500 hr,	*m*	—	5.00	—
	B	—	71.5	—
121°C/1000 hr,	*m*	—	5.39	—
	B	—	74.2	—

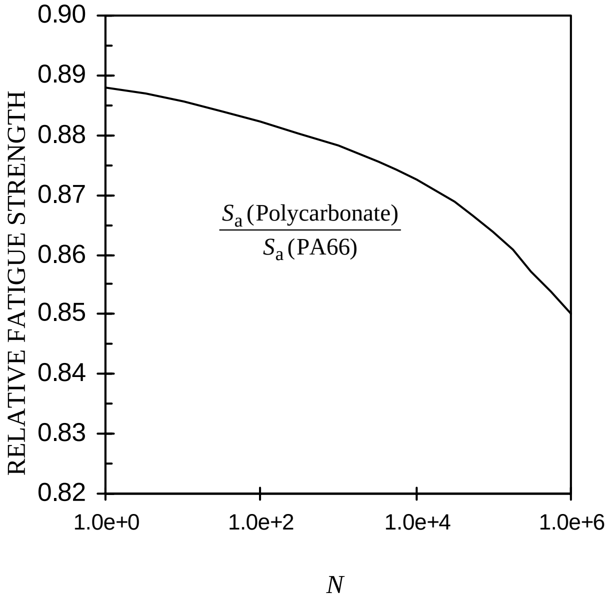

Figure 1. Relative fatigue strength of short glass fiber (40%) reinforced thermoplastics[4]. S_a = stress amplitude = $(S_{max} - S_{min})/2$, used in here to define the fatigue strength. S_{max} and S_{min} are the maximum and minimum stress, respectively.

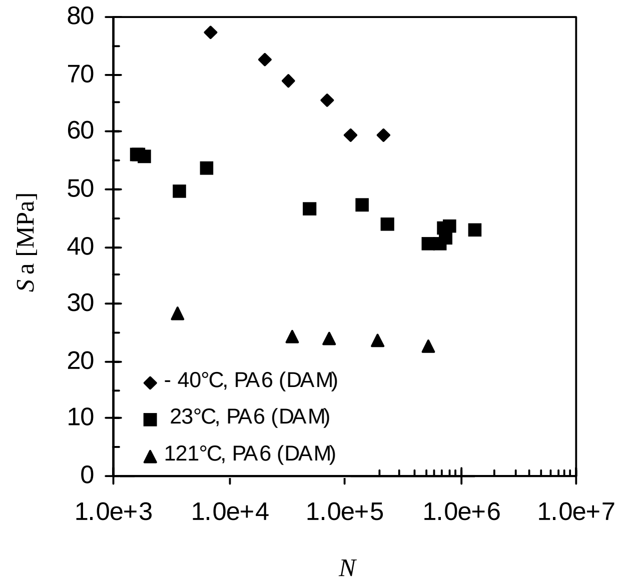

Figure 3. Effect of temperature on the tensile-tensile fatigue behavior of short glass fiber reinforced PA6.

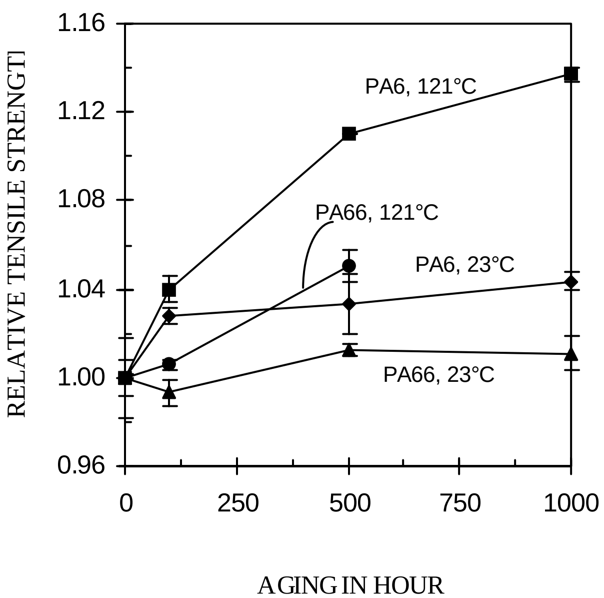

Figure 2. Effect of aging on the relative static tensile strength of polyamide 6 and 66. (Relative tensile strength = (tensile strength of aged material) ÷ (tensile strength of DAM material))

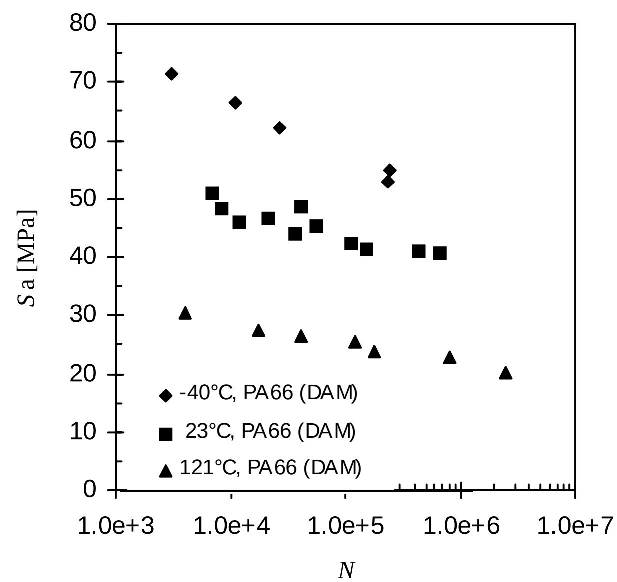

Figure 4. Effect of temperature on the tensile-tensile fatigue behavior of short glass fiber reinforced PA66.

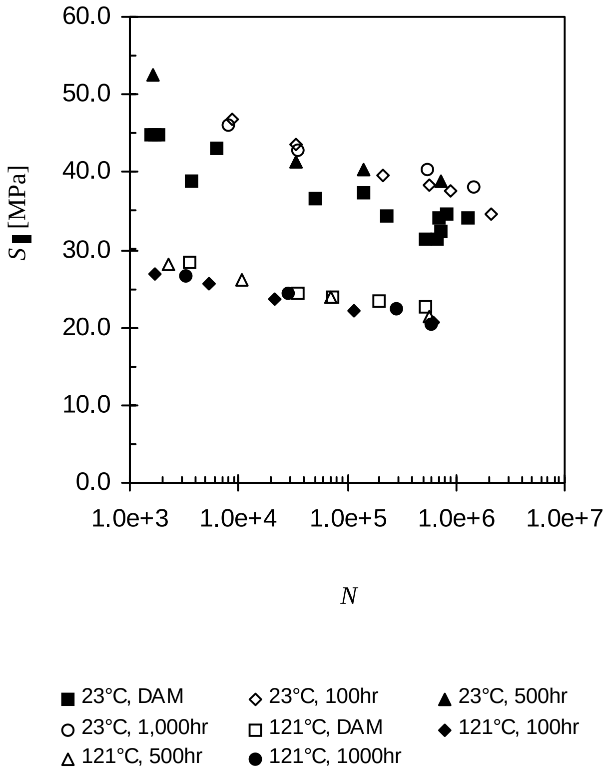

Figure 5. Effect of aging on the tensile-tensile fatigue behavior of short glass fiber reinforced PA 6.

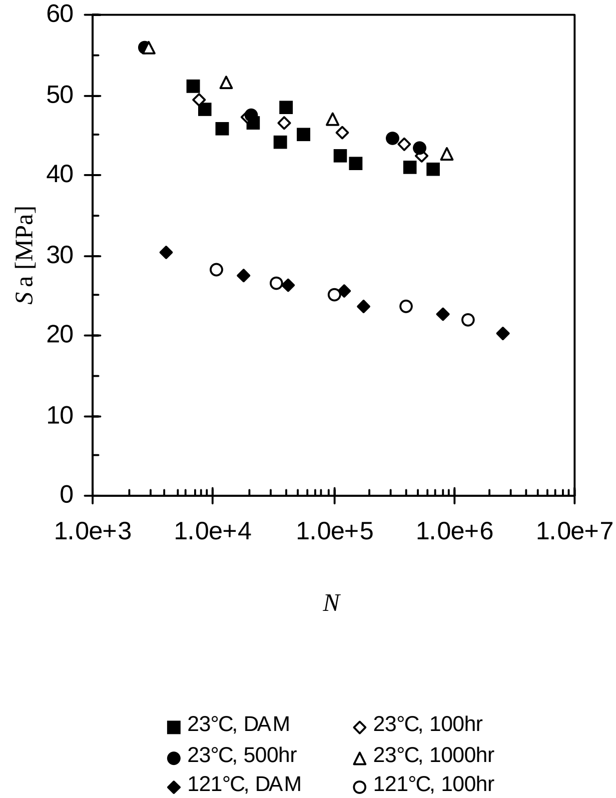

Figure 6. Effect of aging on the tensile-tensile fatigue behavior of short glass fiber reinforced PA66.

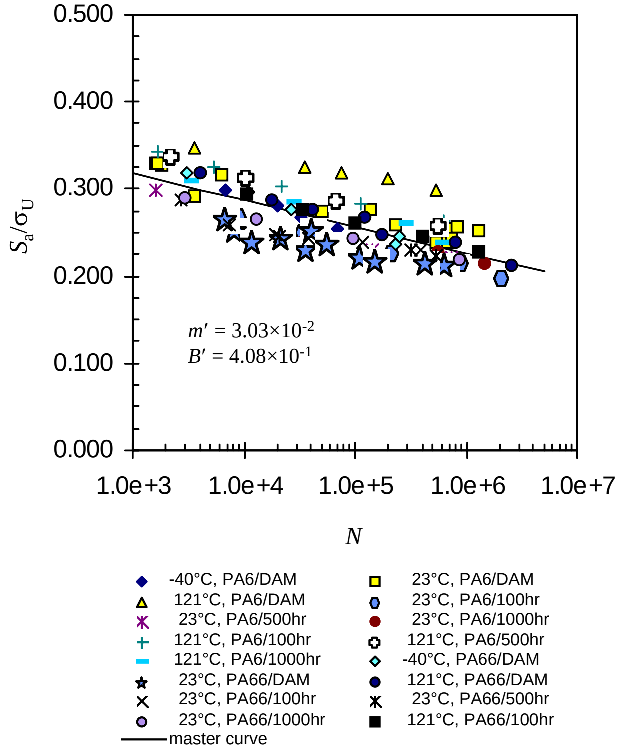

Figure 7. Master curve for PA6 and 66 thermoplastics, indicating a close relationship between the fatigue strength and static tensile strength of the materials. m' and B' are material parameters defined in eq. (2).

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