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Experimental study of the ratcheting behavior and ultra-low-cycle fatigue of a polyamide 66

Rônei Ferreira Silva, Camila Ranucci de Luca, João Laredo dos Reis and Heraldo da Costa Mattos

Universidade Federal Fluminense, Graduate Program in Mechanical Engineering, Laboratory of Theoretical an Applied Mechanics. Rua Passo da Pátria 156, 24210-240, Niterói, RJ, Brazil

Abstract: The present work is concerned with the experimental study of the ultra-low-cycle fatigue of a Polyamide 66. Load-unload fatigue tests under controlled force above the proportional limit were performed at different frequencies. The experimental results indicate that the behavior elasto-viscoplastic rather than viscoelastic: The elastic properties are rate-independent while the plastic behavior is strongly rate-dependent. In this case, the number of cycles until rupture tends to be smaller or lower loading frequencies. However, it is verified that very small variations of the mechanical properties beyond the proportional limit strongly affects the fatigue behavior.

Keywords: Polyamide 6.6, Load-unload tests, Elasto-viscoplasticity, Ratcheting, Fatigue

INTRODUCTION

Thermoplastic polymers are being used throughout the years in infrastructures exposed to harsh environments involving high and low temperatures or marine environments. Polyamides or nylons are a type of thermoplastic materials. They are being adopted in engineering applications due to their high stiffness/weight ratio, high strength/weight ratio and corrosion resistance. Industrial applications include automotive, aeronautical and Oil and Gas industries. There are many studies regarding the effects of temperature and strain rates on the tensile behaviour of polymers (Mota et al, 2018, Costa Mattos et al, 2017, Reis et al, 2015, Reis et al, 2014). Low and high temperatures induce changes in mechanical properties. It is necessary, therefore, to carry out a mechanical characterization over the complete range of temperatures that can be reached during the operational life of components made of these materials.

The present work is concerned with the experimental study of the ultra-low cycle fatigue behavior of Polyamide 6.6 (Nylon 66 or PA 66). Load-unload fatigue tests under controlled force above the proportional limit were performed at different frequencies. Despite there is not a precise definition of "ultra-low cycle fatigue" for polymers, in the present work it will be assumed that the fatigue occurs in an "ultra-low" numbers of cycles if the lifetime is below 200 cycles. In these tests, the material exhibits a hysteresis behavior, which leads to a progressive accumulation of deformation. The experimental results indicate that the behavior is elasto-viscoplastic rather than viscoelastic: the elastic properties are rate-independent while the plastic behavior is strongly rate-dependent. The proportional limit and the ultimate strength are higher for higher rates. In this case, the number of cycles until rupture tends to be smaller for lower loading frequencies. However, it is verified that a very small variation of the mechanical properties beyond the proportional limit strongly affects the fatigue behavior and the scatter of results (lifetime in cycles) is huge. Due to the fabrication processes of mechanical elements made of PA 66 (such as the test specimens), it is impossible to avoid such a small variation of the mechanical properties. Thus, the main result is that ultra-low cycle fatigue in this Polyamide is a very unstable phenomenon and that loading cycles under controlled stress above the proportional limit must be avoided.

Material and experimental procedures

One type of Polyamide was considered in this study: PA66 used in different industrial application such as water drain valves and car intakes. Specimens were injection moulded from this grade. The Polyamide was injected in a mould to prepare test specimens according to ASTM D 638-10 [6]. Fig. 1 shows the injection mould and a typical test specimen. The cross-section of each specimen is 12.8 mm X 4 mm and the useful length is 93.4 mm.

All tests were performed in a Shimazu AG-X universal testing machine at room temperature. To verify the rate-dependency, initially it was performed a monotonic tensile test with prescribed strain. The prescribed strain history is shown in Fig. 2. This tensile test was performed in steps with three different strain-rates: 6.5E-4 s^{-1}, 6.5E-3 s^{-1} and 6.5E-2 s^{-1}. The ASTM D 638 standard define a tensile test with only one elongation 5 mm/min, corresponding, in this case, to a strain rate of 6.5E-3 s^{-1}.

After this preliminary tensile test, fatigue tests with prescribed force using a triangular load wave shape with a maximum load of 2150 N ($\approx$42 MPa, 80% of the mean rupture load obtained in tensile tests using the ASTM D 638 standard (prescribed strain rate of 5 mm/s) considering 3 different frequencies: 4.65E-4 Hz, 6.98E-4 Hz and 9.30E-4 Hz, corresponding to constant rates of (+/-) 2 N/s, 3 N/s and 4 N/s. Above these frequencies the fatigue life was above 200 cycles.

Figure 1 – Injection mold PA66 and typical test specimen.

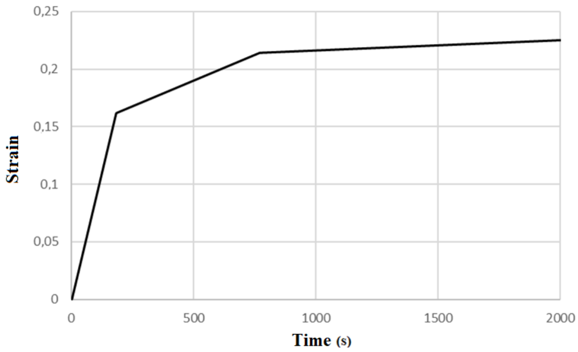

Figure 2: Tensile test. Prescribed loading history

Results and discussion

Tensile test

Fig. 3 presents the stress vs. strain curve obtained using the loading history depicted in Fig. 2. The curves with dashed lines correspond to monotonic tensile tests with prescribed strain rates (6.5E-4 s^{-1}, 6.5E-3 s^{-1} and 6.5E-2 s^{-1}). It is observed a significant rate dependency and that the proportional limit is affected by the loading rate.

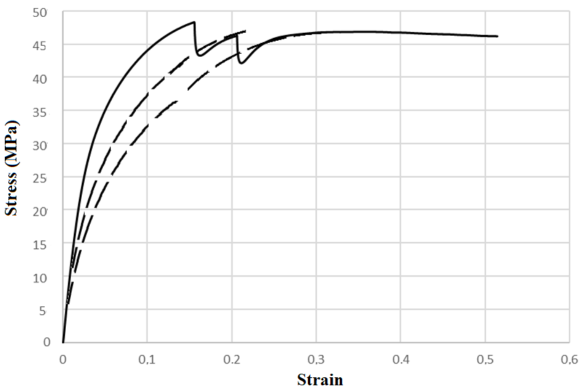

Figure 3: Tensile test with three different loading rates.

Fatigue tests at different frequencies

The results of the fatigue tests, with three tests performed with specimens produced simultaneously, are: 6 cycles, for the frequency of 6.5E-4 s^{-1}Hz; 19 cycles, for the frequency of 6.5E-3 s^{-1}Hz and 96 cycles, for the frequency of 6.5E-2 s^{-1}Hz. The initial stiffness is not significantly affected by the frequency. During repeated loading, polymers responds in three possible ways: adaptation, accommodation and ratcheting. The adaptation response is observed when cyclic stress paths return to a new elastic state. In this case, the initially accumulated plastic strains are dissipated, and the path becomes linear. In the accommodation response, also known as "plastic shakedown", the plastic strains also dissipate, but the steady state is observed as a closed hysteresis loop. In the ratcheting state, the specimen accumulates plastic strains in each cycle. The failure phenomenon in this case is clearly related to the ratcheting behavior and lifetime depends on the accumulated plastic strain and on the energy dissipated per cycle (see Fig. 4).

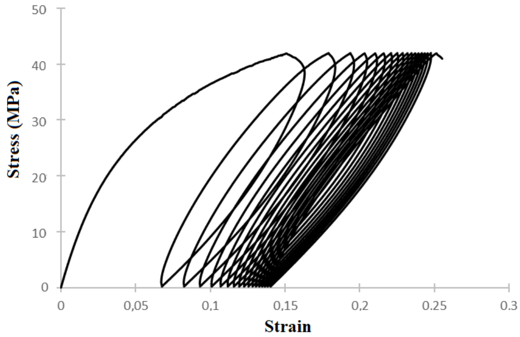

Figure 4: Stress vc strain curve for the frequency of 6.98E-3 Hz.

However, one major problem to perform more tests at the same frequency is that groups of specimens produced by injection have the same elastic properties, but not the same cyclic plastic behavior. In other words, the fabrication process (injection performed by the company Fabrimar) did not assure that the material behavior is the same in all batches. Figure 5 presents three tests performed with specimens fabricated in different batches, showing a huge dispersion in the lifetime.

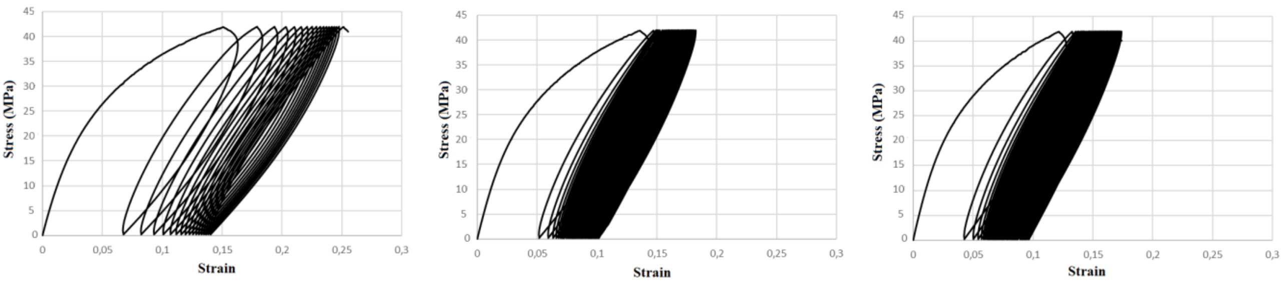

Figure 5: Fatigue tests using the frequency of 6.98E-3 Hz. First test 19 cycles, second test 165 cycles, third test 273 cycles. Specimens from different batches.

CONCLUSION

Experimental results show that the failure behavior of PA-66 specimens is strongly dependent on the loading frequency. Ultra-low-cycle fatigue was observed when ratcheting occurs and is apparently associated to the energy dissipated per cycle of loading (area of the stress vs strain curve in a cycle). It is observed an accumulation of strain at each cycle, de maximum deformation at failure is much smaller than the observed in a monotonic tensile test (above 100%, what characterizes a superplastic behavior). Since, in a load-unload test, the area of the stress vs strain curve in a given cycle tents to be bigger for lower frequencies, the energy dissipation per cycle is bigger and lifetime tends to be smaller. However, due to the fabrication process, the cyclic plastic behavior of the specimens is different for each batch, and thus there is a huge dispersion in the results.

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