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Research Article

Investigation of Thermal Fatigue Behavior for HDPE Composites Reinforced by Nano Alumina

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ABSTRACT

High-Density Polyethylene (HDPE) like other thermoplastics has low mechanical properties which limits its range of applications, especially under the influence of dynamic loads and high temperatures. Therefore, as one of the highly attractive approaches for improving mechanical properties, nanomaterials have been used as reinforcement materials in polymer matrix composite. The present study focuses on the role of nanomaterials on the mechanical properties and fatigue resistance of high-density polyethylene reinforced with (1, 2, and 3%) nano alumina oxide at a range of testing temperatures between 20 and 60ºC. The results manifested that the addition of nano alumina oxide improves the strength of base polyethylene and increases the fatigue resistance by (63.7%, 146.5%, and 228.4%), (69.25, 163.5 and 202.8) and (94%, 214.8% and 290.3) at (20. 40 and 60°C), respectively in cooperation with the pure high-density polyethylene. In addition, as the applied testing temperature increases, the fatigue resistance in all test specimens decreases. It was found that the highest fatigue resistance occurred at (HDPE+3%Al2O3) composite due to the good distribution of nano Al2O3 within the HDPE base which led to a better crack propagation prevention than other composites.

1. Introduction

Thermoplastics and their composites occupy a great position in industrial applications due to their unique properties, such as low weight, low cost, chemical and thermal stability, and easy manufacturing. However, their low mechanical properties have limited their field of usage [1]. One of the most attractive polymers is Polyethylene, it has been used for pipe manufacturing due to its flexibility and thermal stability. However, Polyethylene like other thermoplastics has a low fatigue resistance, especially when interacting with other effects, such as heat or fraction [2].

Recently, researchers have focused on the improvement of the mechanical and thermal properties of polymers by adding alumina particles as a reinforcement material. For instance, N. Akmil et al. [3] found that the addition of treated nano alumina to the high-density polyethylene/hydroxyl apatite composite using radiation can enhance the tensile strength of the prepared composite. Mohammad T. H. Mosavian et al. [4] studied the thermal properties of HDPE reinforced with micro alumina particles. The results showed that no significant improvement in all thermal properties could be achieved. In addition, Swain et al. [5] examined the influence of nano silica and nano alumina addition to Polyurethane as

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reinforcement materials on their mechanical and thermal properties. A clear enhancement in tensile strength of 41% and 50% of pure polyurethane due to the addition of 1% nano-silica and nano alumina respectively was recorded. Vijay et al. [6] assessed the influence of nano alumina-reinforced Epoxy resin on fatigue behavior. The results revealed that the addition of nano-alumina up to 1% wt improved the tensile strength, Young's modulus, and fatigue life by 26%, 14%, and 75%, respectively compared with pure epoxy. Moreover, Djebli et al. [7] studied the influence of loading sequence on fatigue damage behavior for high-density polyethylene (HDPE) and estimated the fatigue life for the prepared material. Two loading sequences, high-low and low-high were applied to the test specimens. It was found that the Miner rule is a suitable method to predict fatigue damage models in HDPE polymer. JLS Ngu et al. [8] investigated the effect of adding up to 5 wt.% nano-alumina to low-density polyethylene (LDPE) on the thermal properties of the prepared composite. The results showed that the increase in nano alumina content improves the thermal stability of the prepared composite in comparison to the matrix material. In addition, a clear increase in glass transition temperature (Tg) values was observed. A. Fathy et al. [9] found that the use of nano alumina as reinforcing material to glass fiber Epoxy composite improves the tensile strength by 54.76% in comparison to glass fiber epoxy composite. As well as the increase in nano alumina content up to 3% enhances the fatigue resistance. Othman Y. Alothman et al. [10] studied the role of surface-treated nano alumina with 1.5, 3, and 6 wt.% on the viscoelastic behavior of LDPE using injection technique as a composite material preparation method. The results manifested by an increase in the modulus of elasticity and hardness when 1.5 wt.% of nano alumina was added. Sergio Augusto B. Lins et al. [11] studied the thermal and mechanical properties of HDPE/Al2O3 and HDPE/GF-Al2O3 composites. It was found that no improvement in thermal properties and a decrease in mechanical properties can be achieved due to the addition of nano alumina. On the other hand, a light enhancement in both thermal and mechanical properties was recorded in HDPE/GF-Al2O3 due to the poor adhesion in the prepared composite. H. Shahrajabian and F. Sadeghian [12] found that the addition of nano alumina up to 3 wt.% to a blended matrix consisting of high-density polyethylene and recycled polyethylene terephthalate enhanced the mechanical properties, such as tensile strength, Young's modulus, and energy absorption. Mohamed Saleh et al. [13] studied the effect of nano alumina content on the thermal and tensile properties of HDPE composites, and the outcomes elucidated that the good dispersion of nanofillers without agglomeration and filler content less than 5 wt.% gave better tensile properties in comparison with the higher filler content with an improvement in the thermal properties in all the prepared composites. M. Di Maro et al. [14] demonstrated the influence of alumina and zirconia particles on the mechanical and tribological properties of hybrid HDPE composites. The results portrayed an enhancement in mechanical and tribological properties for the prepared composite due to the good dispersion of the filler materials.

From the aforementioned literature, it can be noticed that the influence of nano alumina particles on the fatigue behavior of HDPE composites has received very little attention. As well as the addition of nano alumina particles was limited up to 5% to prevent agglomeration within the matrix. Therefore, the aim of this paper is to investigate the influence of nano alumina particles with (1,2, and 3% wt) on the fatigue resistance of high-density polyethylene at room and high temperatures.

2. Materials and Methods

2.1. Materials

High-density polyethylene (HDPE) was used as a matrix material while, nano alumina (Al_2O_3) particles with 1%, 2%, and 3% wt. (Purity :> 95%, diameter: 25-30 nm, length: 25-40 μm) were used as reinforcement materials. The prepared composite rods with a diameter of 10 mm and different nano alumina contents were produced by Guangzhou Engineering Plastic Industries Group Co. Ltd. Using an injection technique with a two-stage injection molding machine. In order to reveal the distribution of nano alumina filler within the HDPE matrix, a transmission electron microscopy (TEM) test was conducted. No agglomerations of nanofillers were seen in any prepared composites as shown in Fig. 1 (a, b, and c). This indicates a good filler dispersion within the matrix material.

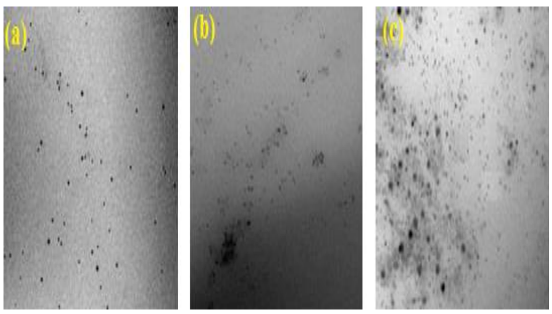
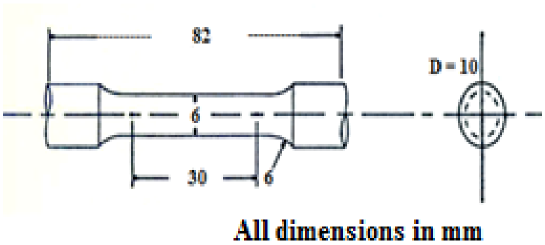


Fig. 1. TEM images for: (a) HDPE+1%Al_2O_3, (b) HDPE+2%Al_2O_3, and (c) HDPE+3%Al_2O_3

2.2. Tensile Test

In order to perform the fatigue test, a tensile test was performed first for all pure and reinforced HDPE composites to obtain the mechanical properties such as yield stress, tensile strength, and Young's modulus. These results were used as input data for the fatigue test. Tinius Olsen universal testing machine was used to fulfill the tensile test. The test specimens that were used in the tensile test are illustrated in Fig. 2. The tests were performed with a speed of 5 mm/min according to ASTM D638-14 [15]. Five test specimens were tested and the average value of each property was considered.

(a)



(b)

Fig. 2. Standard and actual tensile test specimens

2.3. Fatigue Test

A rotating bending fatigue test machine was designed to predict the thermal effect on the fatigue behavior for different kinds of polymers by attaching a small furnace with a control panel to the test machine, as displayed in Fig. 3. This furnace was structured by double steel wall sheets and stuffed by five layers of woven glass fiber to prevent heat dissipation to the surrounding. It was supplied by an electrical heater with 2000 W and a K-type thermocouple for controlling the temperature level.

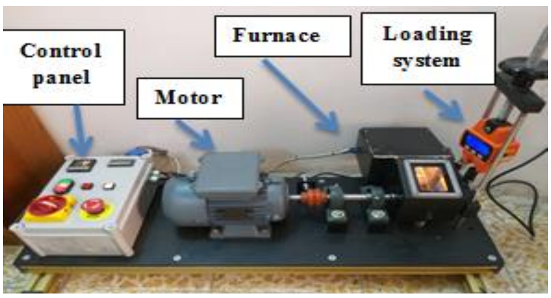
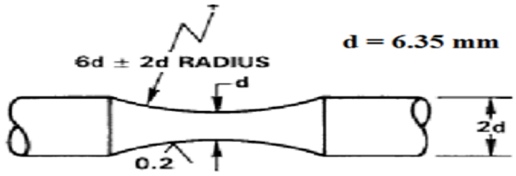
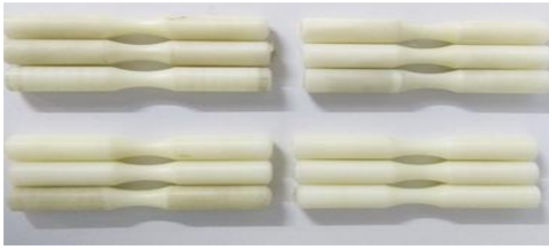


Fig. 3. Fatigue test machine

Fatigue test specimens were prepared in accordance with the ASTM E606 fatigue test standard for polymers illustrated in Fig. 4 (a and b) [16]. The specimen was fixed within the test machine as a cantilever beam and rotated at 1200 rpm while the stress was applied to the free end of the test specimen by the loading system.



(a)



(b)

Fig. 4. Standard and actual fatigue test specimens

3. Results and Discussion

3.1. Tensile Test Results

To assess the effect of nanoparticles on the mechanical properties of HDPE and their composite, a tensile test was performed. The stress-strain curves of each one are illustrated in Fig. 5, and the average value of each property was calculated and listed in Table 1.

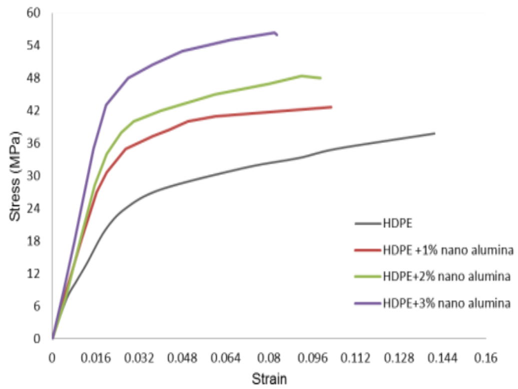


Fig. 5. The stress-strain curves of HDPE and their composites

From the results, it can be seen that the addition of nano Al_2O_3 particles with 1, 2, and 3 wt.% improved the yield stress value by 29%, 46%, and 73%, respectively. In addition, the ultimate stress and Young's modulus values improved by (12.7%, 27.8%, 49%) and (44.7%, 120%, 175%), respectively.

Table 1. The mechanical properties of HDPE and their composites

Material	Yield stress (MPa)	Ultimate stress (MPa)	Young's modulus (GPa)
Pure HDPE	24.37 ± 0.12	37.80 ± 0.22	0.85 ±0.02
HDPE +1%Al_2O_3	31.40 ± 0.17	42.63 ± 0.16	1.23 ± 0.05
HDPE +2%Al_2O_3	35.63 ± 0.09	48.34 ± 0.21	1.87 ± 0.03
HDPE +3%Al_2O_3	42.2 ± 0.15	56.33 ± 0.13	2.34 ± 0.03

The good disruption of nanofillers within the HDPE matrix with limited agglomerations as shown in Fig. 1 leads to the improvement of the cross linkages between the matrix and the reinforcement materials and an increase in its ability to sustain higher applied loads at room and higher temperatures. As a result, all the mechanical properties of the prepared materials are improved. A similar enhancement in the mechanical properties was seen by H. Shahrajabian and F. Sadeghian [12] and M. Di Maro et al. [14] when evaluating the influence of nano Al_2O_3 on the mechanical properties of HDPE composites.

3.2. Fatigue Test Results

To specify the number of cycles till failure due to applying a dynamic load on any material, the (S-N) curve was plotted in a log-log form. From this curve, the correct applied stress can be estimated to prevent the failure due to the fatigue. The yield stress value obtained from a tensile test is used as a reference value to select the applied stress in the fatigue test. Nine applied stress values below the yield stress were selected to perform the thermal fatigue test. Three test specimens were tested for each material for the selected stresses and different temperatures (20, 40, and 60 ºC) and the average value of the number of cycles to failure was considered. All the applied stress values varied between 0.9 and 0.5 of yield stress within the high cycle fatigue regime. The log-log (S-N) curves for all tested materials are illustrated in Fig. 6, Fig. 7, and Fig. 8.

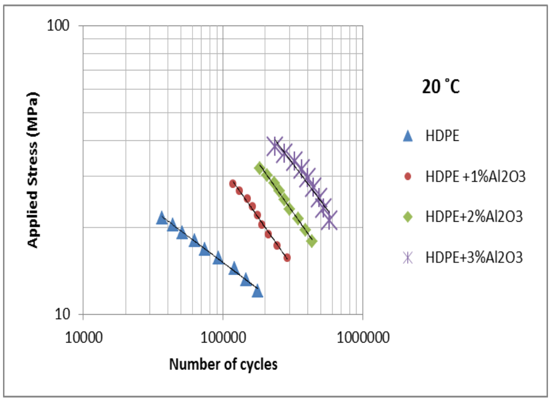


Fig. 6. S-N curves of HDPE and their composites at 20°C

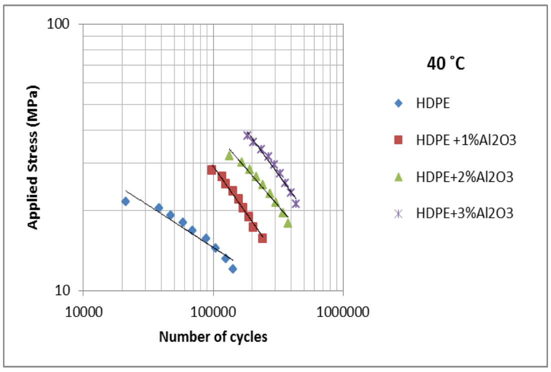


Fig. 7. S-N curves of HDPE and their composites at 40ºC

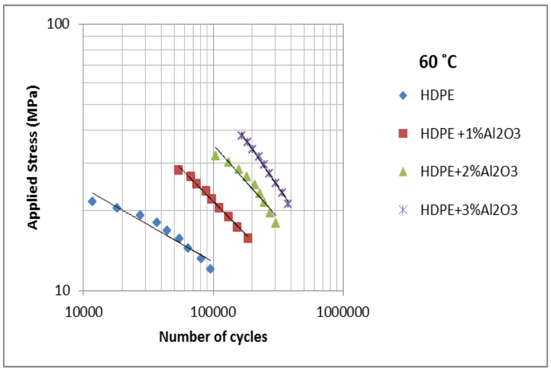


Fig. 8. S-N curves of HDPE and their composites at 60°C

As presented in Fig. 6 to Fig. 8, the addition of (1, 2, and 3 wt.%) nano Al_2O_3 leads to enhance fatigue resistance clearly by 63.7%, 146.5%, and 228.4%, respectively, compared with pure HDPE at 20 °C. A good improvement in fatigue resistance was seen at 40 and 60 °C due to nano-reinforcing material effects by (69.25, 163.5, and 202.8) and (94%, 214.8%, and 290.3), respectively, compared with HDPE. The nano alumina fillers played an important role in enhancing the fatigue resistance in HDPE at room and elevated temperatures by prohibiting the initiated microcracks from propagation under cyclic loading. The improvement in microstructure retards the microcracks from unity, which leads to a delay in the dramatic fatigue failure as a result of crack propagation. In order to compare the obtained results of the fatigue test and due to the absence of research associated with the influence of nano alumina fillers on fatigue behavior in HDPE, it can rely on research work that investigated the fatigue behavior for other polymers reinforced with nano alumina. As seen by V. Verma and C. Sharma [17] and Su Zhao et.al [18] with the presence of nano alumina fillers up to 3%, the fatigue life was increased as a result of good distribution of nanofillers within the matrix phase by preventing the propagation of cracks.

4. Conclusions

Based on the obtained experimental results, it can conclude the following:

1) The increasing of nano Al_2O_3 content in HDPE improves all the mechanical properties.
2) The increase in applied stress and testing temperature leads to a reduction in the fatigue life for pure and reinforced HDPE.
3) The addition of nano Al_2O_3 increases the fatigue resistance by 63.7%, 146.5%, and 228.4% compared with pure HDPE at 20ºC. However, at 40 and 60ºC the fatigue resistance was increased by (69.25, 163.5, and 202.8) and (94%, 214.8%, and 290.3) respectively in comparison to pure HDPE.
4) The highest fatigue resistance occurs at (HDPE+3%Al_2O_3) composite due to the good distribution of nano Al_2O_3 within the HDPE base which prevents the crack propagation better than other composites.

Nomenclature

HDPE	High Density Polyethylene
Al_2O_3	Alumina

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Conflicts of Interest

The authors have no conflicts of interest to declare.

References

[1] Rajesh Kumar, S., Muthu, K. and Bakkiyaraj, V., 2016. Development of thermo plastic gears for heavy duty applications using APDL. *International journal of trend research and development*, 3(2), pp.304-309.

[2] Shaari, N.Z.K., Abd Rahman, N., Taha, A.R., Alauddin, S.M. and Akhbar, S., 2021, February. Enhancement of strength and flexibility of high-density polyethylene using rubber leaves. In *IOP Conference Series: Materials Science and Engineering* (Vol. 1053, No. 1, p. 012029). IOP Publishing.

[3] Akmil, N., Abdullah, L.C., Ahmad, M. and Zaman, D.K.M., 2011. Nano-Alumina and Radiation Effect on the Mechanical Properties of High Density Polyethylene/Hydroxy Apatite Composite. *Key Engineering Materials*, 471, pp.121-126.

[4] Mosavian, M.T.H., Bakhtiari, A. and Sahebian, S., 2012. Influence of Alumina Particles on Thermal Behavior of High Density Polyethylene (HDPE). *Polymer-Plastics Technology and Engineering*, 51(2), pp.214–219.

[5] Swain, S., Sharma, R. A., Bhattacharya, S. and Chaudhary, L., 2013. Effects of Nano-silica/Nano-alumina on Mechanical and Physical Properties of Polyurethane Composites and Coatings. *Transactions on Electrical and Electronic Materials*, 14(1), pp.1–8.

[6] Verma, V., Shukla, D.K. and Kumar, V., 2014. Estimation of fatigue life of epoxy-alumina polymer nanocomposites. *Procedia materials scienc*e, 5, pp.669-678.

[7] Abdelkader, D., Mostefa, B., Abdelkrim, A., Abderrahim, T., Noureddine, B. and Mohamed, B., 2015. Fatigue life prediction and damage modelling of high-density polyethylene under constant and two-block loading. *Procedia Engineering*, 101, pp.2-9.

[8] Ngu, J.L.S., Noshida, I., Akmil, M., Luqman Chuah A., and Chantar Thevy, R., 2012. Thermal properties of low-density poly-ethylene/ALPHAalumina nanocomposites. *Journal of Thermoplastic Composite Materials*, 25(4), pp.415–426.

[9] Fathy, A., Shaker, A., Hamid, M.A. and Megahed, A.A., 2017. The effects of nano-silica/nano-alumina on fatigue behavior of glass fiber-reinforced epoxy composites. *Journal of Composite Materials*, 51(12), pp.1667-1679.

[10] Alothman, O.Y., Alshammari, B.A. and Fouad, H., 2017. Effect of Aluminum Oxide Nanoparticles on Nanomechanical and Viscoelastic Properties of Low Density Polyethylene Composites. *Nanoscience and Nanotechnology Letters*, *9*(12), pp.1891-1898.

[11] Lins, S.A.B., Rocha, M.C.G. and d'Almeida, J.R.M., 2019. Mechanical and thermal properties of high-density polyethylene/alumina/glass fiber hybrid

composites. *Journal of Thermoplastic Composite Materials*, 32(11), pp.1566-1581.

[12] Shahrajabian, H. and Sadeghian, F., 2019. The investigation of alumina nanoparticles' effects on the mechanical and thermal properties of HDPE/rPET/MAPE blends. *International Nano Letters*, 9(3), pp.213-219.

[13] Saleh, M., Al-Hajri, Z., Popelka, A. and Javaid Zaidi, S., 2020. Preparation and characterization of alumina HDPE composites. Materials, 13(1), p. 250.

[14] Di Maro, M., Duraccio, D., Malucelli, G. and Faga, M.G., 2021. High density polyethylene composites containing alumina-toughened zirconia particles: Mechanical and tribological behavior. *Composites Part B: Engineering,* 217, p.108892.

[15] ASTM D638-14, 2015. Standard test method for tensile properties of plastics. *ASTM International*, West Conshohocken.

[16] ASTM E-606, 2006. Standard recommended practice for constant-amplitude fatigue test. *ASTM International*, West Conshohocken.

[17] Verma, V. and Sharma, C., 2020. Fatigue behavior of epoxy alumina nanocomposite–role of particle morphology. *Theoretical and applied fracture mechanics*, 110, pp. 10-28.

[18] Zhao, S., Schadler, L.S., Hillborg, H. and Auletta, T., 2008. Improvements and mechanisms of fracture and fatigue properties of well-dispersed alumina/epoxy nanocomposites. *Composites Science and Technology*, *68*(14), pp.2976-2982.