Fatigue Life Prediction of Injection Molded Polymer Materials

Syamsul Hadi[1], Agus Hardjito[2], Hangga Wicaksono[3], Tri Setyo Aji Cahyono[4], Wirawan Wirawan[5], and Zakki Fuadi Emzain[6]

[1,2,3,4,5,6] Mechanical Engineering Department, State Polytechnic of Malang, Jl. Soekarno-Hatta 9, Malang 65143, Indonesia

syamsul.hadi@polinema.ac.id or syampol2003@yahoo.com

Abstract. The problem of this study is the unknown fatigue life (N) prediction of polymer materials, especially plastic specimens made from polypropylene (PP), low density polyethylene mixed with scrap (low density polyethylene/LDPE + 70 % scrap), high impact polystyrene (HIPS), acrylonitrile butadiene styrene (ABS), and polystyrene (PS). The aim of the research was to obtain predictions of N from fatigue test results for 5 types of materials, PP, LDPE + 70 % scrap, HIPS, ABS, and PS. The research method includes making injection molds for fatigue test specimens according to standard shapes and dimensions, injection molding, specimen preparation, fatigue testing using an integrated rotating bending fatigue testing machine (IRBFTM), analysis of fatigue test results in the form of a bending stress curve (S) to the fatigue life (N). The results of the fatigue test show that the N at 2200 rpm speed testing for PP materials in the range S 70 to 230 MPa is achieved at 15 $x10^5$ Cycles, HIPS is 18 $x10^4$ Cycles, ABS is 12 $x10^5$ Cycles, and PS materials is 16 $x10^4$ Cycles, and the LDPE specimen materials mixed with its 70 % scrap cannot be tested for fatigue because they are very ductile or fatigue resistant.

Keywords: Fatigue Life, Molded, Polymer, Prediction, Specimen.

1 Introduction

Fatigue test specimens are generally made using a CNC (Computer Numerical Control) Lathe because it takes a radius shape in the center in the direction of the longitudinal axis of the specimen. Materials that are not too ductile and strong can be worked using a copy lathe available in the integrated rotating bending fatigue testing machine (IRBFTM), but for thermoplastic materials, they can be prepared more easily and faster by injection in one mold sets. Five plastic materials have been injected and used in the research including polypropylene (PP), low density polyethylene mixed with its scrap (LDPE + 70 % scrap), high impact polystyrene (HIPS), acrylonitrile butadiene styrene (ABS), and polystyrene (PS).

Plastic materials can be made into composites with various combinations of fibers and matrices. Composite polymer materials are widely used in the automotive industry to

R. Andrie Asmara et al. (eds.), *Proceedings of the 5th Annual Advanced Technology, Applied Science, and Engineering Conference (ATASEC) 2023*, Advances in Engineering Research 229,
https://doi.org/10.2991/978-94-6463-358-0_24

reduce vehicle weight and production costs in order to meet environmental requirements [1]. Automotive fuel efficiency is becoming an increasingly sought after demand and automotive production costs are kept down as much as possible so that products can be more competitive in the market. The mechanical properties of recycled polypropylene plastic specimens (standard ASTM D 638, type II) show a yield strength of about 16 MPa, an ultimate tensile strength of 20 MPa, and a modulus of elasticity of 296 MPa [2]. The yield strength of recycled PP may have different values due to differences in the quality of the raw material and processing. HIPS materials are among the toughest polymers which are well known for the presence of a rubber phase. The Charpy hammer impact angles at 5, 10, 15, 20, and 25° produce varying fracture characteristics with high crack propagation rates at high impact angles with lower durability, and vice versa [3]. The crack propagation rate is affected by the impact angle, the number of collisions and the distance the specimen rests in the impact test. The properties of the recycled PP/LDPE mixture do not change until the composition reaches 25% by weight, which means that the mixture can be used in the same way as pure recycled PP [4]. The sorting process of recycled PP and recycled LDPE can be eliminated, thereby saving process costs.

The 3D printed ABS fatigue test specimens using fused deposition modeling (FDM) techniques compared to molded specimens. Tensile test molded specimens (standard ASTM D638) were made to obtain tensile strength. The fatigue characteristics at several percentages of the tensile strength results show that the molded specimens have a higher fatigue life (N) than 3D printing at all loads with N for 40, 60, and 80 % of the tensile strength are 911, 2645 and 26948 cycles respectively [5]. Bonding within the injection molded material was better than 3D printed interfacial bonding in fatigue tests. The fatigue performance of PC-ABS and ABS that were tested in comparison at high temperatures (85 °C) and low temperatures (-27 °C) showed that the PC-ABS material experienced a slight increase at low temperatures, but at high temperatures, it decreased by about 10 %, ABS showed reduction of more than half of the fatigue limit at room temperatures [6]. The N limit of PC-ABS at high temperatures is nearly double that of ABS, and at low temperatures the two materials are nearly the same. Polymer composite materials have been used as key components in the transportation and alternative energy industries, because these materials are lighter than metals and their alloys, but can maintain proportional strength and durability [7]. As with concrete composites, metal composites, composites from nature such as trees, humans, animals which are composed of fibers and matrices which have an important role as components of a system have been widely used in various functions because of the advantages of certain strengths and durability than others. Polymer-related materials are increasingly being produced for various needs through the FDM or known as additive manufacturing processes, due to their superiority in the manufacture of complex shapes and structures at low overhead costs [8]. The advantage of being able to produce various shapes and complex structures at affordable costs makes FDM increasingly in demand. The self-heating effect is considered a catastrophic phenomenon in polymers and polymer-matrix composites (PMCs) due to fatigue or vibration loads. This phenomenon can increase the temperature of the structure due to its low thermal conductivity. Thermal stresses due to increased temperature and differences in the coefficient of thermal expansion (CTE) of the fiber and adjoining polymer matrix can initiate and/or accelerate structural damage resulting in sudden fatigue failure [9]. An increase in temperature due to fatigue loads can initiate the separation of fibers and matrix from the polymer composite which continues to propagate and eventually causes structural failure. The 3D printing parameters affect the fatigue properties of a component resulting from fusion filament fabrication (FFF) showing the flexural fatigue performance of the FFF component in Y direction printing which has the highest fatigue strength which decreases followed by printing in the X direction and Z direction [10]. The 3D printing parameters of FFF components on fatigue properties, apart from the printing direction are also influenced by many parameters, such as nozzle diameter, infill pattern, and the orientation of the raster rectilinear angle.

The injection molding mixture of PP/PET was prepared in a sample weight ratio of 70/30 at three injection molding temperatures of 210, 230, 280 ºC whereby the injection molding mixture at 280 ºC degrades the mechanical properties, because the material loses its original morphology and the polyethylene terephthalate (PET) phase melts again accompanied by coalescence [11]. Injection molding of PP/PET 70/30 at a temperature of 280 ºC reduces its mechanical properties. PET upcycling from milk bottles can be carried out through reactive extrusion which leads to increased fatigue properties compared to PET from recycling, although the properties of extruded reactive PET are still less than pure PET, but sufficient to make new products in saving resources and reduce environmental impact [12]. Reactive extrusion from PET bottle materials can be used for upcycling to save raw materials and not increase environmental pollution. PP/wood flour (WF) composites were prepared by combining WF with and without maleic anhydride and peroxide (MAPO) into PP impregnated with cellulose nanofibers. Fatigue analysis of PP/WF composites shows 95 % confidence lower band ensuring 95 % survivability which can be used as an index of material reliability for the design of fatigue-safe composites [13]. The melt viscosity of the PP/WF composite decreased significantly with increasing MAPO mixing time at 140 ºC, but did not change significantly at 180 ºC. Expandable polystyrene (EPS) is one of the most widely used materials as a protector of items that are especially sensitive to heat, because the thermal conductivity of EPS material is very low. EPS is subject to complex loading, small to high amplitude for a long duration, especially when transported by truck or ship or car. The test results show that with an increase in dynamic loading to a critical level of more than 100 kPa, the EPS compression rate changes from linear to exponential mode [14]. If EPS is subjected to a fatigue load for a long duration, its mechanical properties change to an exponential pattern which affects its N. The use of waste plastics in the production of asphalt binder-mixtures has been widespread due to its economic benefits and environmental effects. High melting point plastics, such as PS, and polyvinyl cloride (PVC) are suitable for the dry process; whereas LDPE, HDPE, PP, and ethylene-vinyl acetate copolymer (EVA), which have low melting points are suitable for wet processing.

Due to cost and application limitations, modification of plastic waste bitumen requires appropriate pretreatment and modification methods [15]. Steps of separation, grinding, mixing, irradiation, modification with additives in plastic waste can improve the asphalt binder-mixture results. Utilization of polymer waste in modified asphalt binder (asphalt cement/AC) with the best LDPE residue of 5% for road pavement construction at a high temperature of 150 ºC with the aim of preventing oxidation of AC and reducing emissions produced at high temperatures. Under cyclic loading, the modified mixture experiences greater stiffness and resistance to permanent deformation than mixing alone, although it is more porous [16]. Modification of the bitumen binder with waste polymer at high temperatures and a certain amount of residue can increase the stiffness and resistance to permanent deformation. The fatigue behavior of PP fiber concrete as measured by the crack length during the flexural fatigue test with three loads with 1 % weight PP fiber greatly increases the resistance to fatigue crack propagation under constant amplitude loading, with a linear model prediction of N is obtained with an estimation error of 36.8-56.5% but with variable amplitude loading, the N prediction damage curve was obtained with an estimation error of 13-15.8% [17]. Calculation of N prediction with a linear model with variable amplitude loading is lower than constant amplitude loading. EPS structural concrete has good stability with dynamic loads and when compared to plain concrete with the same level of strength, the damping ratio of EPS structural concrete is greater (due to its large energy absorbing ability), and its dynamic modulus of elasticity is smaller which means that concrete structural EPS has superior vibration and toughness performance [18]. EPS structural concrete has the ability to absorb large energy, so that the vibration performance and toughness are superior. A combined framework of experimental and numerical efforts can accurately predict the fatigue life of short fiber reinforced components. The framework incorporates engineering tools that enable engineers to predict the fatigue life of engineering plastics, including anisotropy in great detail which includes characterization of failure mechanisms, anisotropy modeling, as well as compensation for local stress concentrations [19]. The combined experimental and numerical prediction model has been tested for short fiber reinforced composites.

The newly developed rotating bending fatigue testing machine was used to test the fatigue behavior of Aluminum 7075 specimens. The results of the two specimens tested simultaneously produced the same results which proved that the equipment was operating properly [20]. A similar rotating bending fatigue testing machine was used in testing the four types of injection molding fatigue test specimens whose results were considered adequate. The aim of the research is to obtain predictions of fatigue life of 5 types of materials that can be achieved for PP, HIPS, ABS, PS, and LDPE+70% Scrap.

2 Materials and Method

The research was carried out using an experimental method through the selection of specimen materials from polymers consisting of PP, LDPE + 70 % Scrap, HIPS, ABS, and PS which were prepared from granular material which was injected into a set of molds from steel using an injection machine in a plastic factory. After the injection molded specimens are cleaned, if there are excess prints, especially on the parting line so that they are cylindrical in shape, they are checked for straightness, and ready for fatigue testing with IRBFTM to obtain S-N curve data and from the fatigue test results are analyzed to obtain conclusions.

Some of the basic physical properties of PP, LDPE, ABS, HIPS, and PS are shown in Table 1 [20], Table 2 [21], Table 3 [22], Table 4 [23], and Table 5 [24].

Table 1. Properties of PP [20]

No.	PP Properties	Remark
1	Melting Point	135 - 165 °C
2	Density	0.898 - 0.908 g/cm^3
3	Chemical Resistance	Excellent resistance to acids, bases and alcohols
4	Flammability	Highly flammable material

5	Yield strength	11- 40 MPa
6	Elongation at break	15 - 700 %
7	Tensile strength	0.4 - 1.6 GPa

Table 2. Properties of LDPE [21]

No.	LDPE Properties	Remark
1	Melting Point	65 - 90 °C
2	Density	0.917 - 0.930 g/cm^3
3	Chemical Resistance	Excellent resistance to acids, bases, alcohols, and esthers
4	Flammability	Flammable material
5	Yield strength	8-22 MPa
6	Elongation at break	200-810 %
7	Tensile strength	120- 550 MPa

Table 3. Properties of ABS high impact grade A [22]

No.	ABS Properties	Remark
1	Melting Point	210-270 °C
2	Density	1.0 - 1.05 g/cm^3
3	Chemical Resistance	Resin
4	Flammability	Flammable material
5	Young modulus	1.79 - 3.2 GPa
6	Elongation at break	10 - 50 %
7	Tensile strength	29.8 - 43 MPa
8	Hardness Shore D	100

Table 4. Properties of HIPS [23]

No.	HIPS Properties	Remark
1	Melting Point	180 - 270 °C
2	Density	1.03 - 1.08 g/cm^3
3	Flexural Modulus	1.9 - 2.3 GPa
4	Young modulus	1.8 - 2.28 GPa
5	Elongation at break	10 - 55 %
6	Tensile strength	20 - 28 MPa

Table 5. Properties of PS [24]

No.	PS Properties	Remark
1	Melting Point	217 °C
2	Density	1.05 g/cm^3
3	Young modulus	3.4 GPa
4	Tensile strength	48 MPa
5	Hardness	50 BHN

The standard fatigue test specimen has a radius of 254 mm (see Fig. 1.)

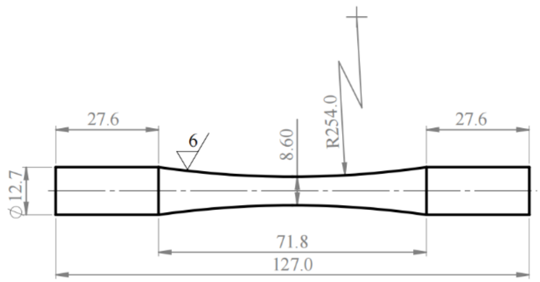

Fig. 1. Standard fatigue test specimens with a radius of 254 mm

To make specimens from PP, LDPE, ABS, HIPS, and PS materials, injection molding is carried out using a set of molds (see Fig. 2).

Fig. 2. A set of molds for manufacturing fatigue specimens from PP, LDPE + 70 % Scrap, ABS, HIPS, and PS materials [25]

Injection molding results for 5 types of polymer materials consisting of PP, LDPE + 70 % Scrap, ABS, HIPS, and PS (see Fig. 3).

Fig. 3. Injection molding results for 5 types of polymeric materials, PP, LDPE + 70 % Scrap, ABS, HIPS, and PS

The integrated rotating bending fatigue testing machine (IRBFTM) was used in the study (see Fig. 4).

Fig. 4. The integrated rotating bending fatigue testing machine (IRBFTM)

The result of recording the number of revolutions from the start of the specimen is installed at the load level in kg on IRBFTM until it breaks which is expressed as the N which is displayed on the monitor screen. The bending stress is calculated using formula (1) to formula (3).

$$S=M.c/I \quad (1)$$

$$M=(F/2)\,(L/2) \quad (2)$$

$$I=\pi d^4/64 \quad (3)$$

where:
M: Flexure moment [Nm];
c: Outer fiber distance or radius of specimen [m];
F: Load (N), in the range of 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 [kg];
L: Horizontal distance between bearings load, fixed for the FATEMACH machine (IRBFTM) is 0.285 [m];
I: Inertia moment (m^4);
d: Diameter in the center of of fatigue specimen length [mm].

The treatment carried out in the fatigue test on polymer specimen materials resulting from injection molding was the difference in the rotational speed of the test on the selected IRBFTM at 1800 rpm, 2000 rpm and 2200 rpm.

3 Results and discussion

After the specimen has broken the results of the fatigue test are shown in several examples (see Fig. 5.)

Fig. 5. Some examples of fatigue test specimens after breaking

The results of the fatigue test of the injection molded polymer material (see Fig. 6 to Fig. 9) are displayed in the form of a flexural stress curve against the number of revolutions until the specimen breaks, the S-N curve.

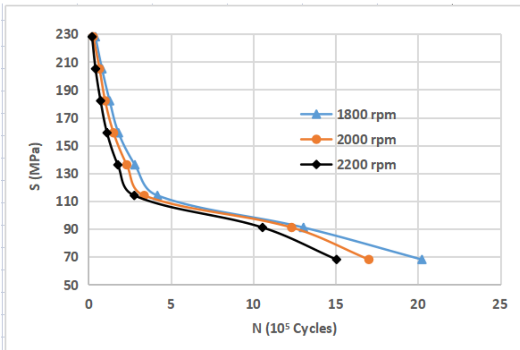

Fig. 6. The S-N curve of PP

The difference in the rotational speed of the fatigue test specimens from PP material shows that with the higher rotational speed of the fatigue test specimens at various levels of bending stress, the tendency for a shorter fatigue life is obtained, this is shown in the S-N curve (see Fig. 6) which is increasingly shifted to the left for 2200 rpm rotation compared to the fatigue test on 2000 rpm and 1800 rpm specimens.

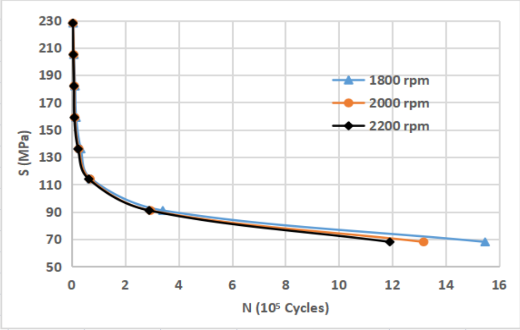

Fig. 7. The S-N curve of ABS

The difference in the rotational speed of the ABS material fatigue test specimens shows that the higher the rotational speed of the specimen at a bending stress above 110 MPa, the fatigue life decreases slightly, but at a bending stress below 110 MPa, the fatigue life tends to be shorter, this has been proven on the S-N curve (see Fig. 7) which at the top of the curve almost coincides and at the bottom it is increasingly shifted to the left at 2200 rpm rotation than the fatigue test on the 2000 rpm and 1800 rpm specimens.

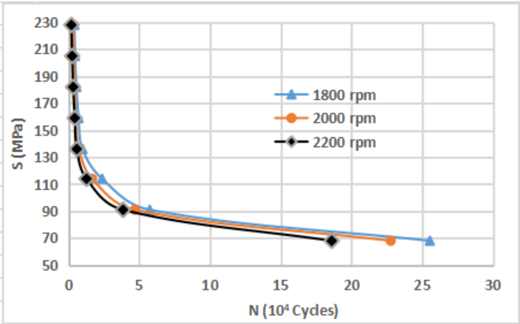

Fig. 8. The S-N curve of HIPS

The different rotational speeds for the HIPS material fatigue test specimens show that the higher the shaft-machine/specimen rotational speed at a bending stress above 150 MPa, the fatigue life decreases relatively slightly, but at a bending stress below 150 MPa, the fatigue life is sufficient decreased, this is expressed in the S-N curve (see Fig. 8) which at the top of the curve line almost coincides and at the bottom it is increasingly to the left at 2200 rpm compared to the fatigue test at 2000 rpm and 1800 rpm.

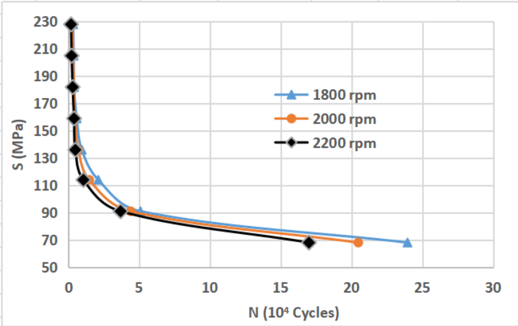

Fig. 9. The S-N curve of PS

The different rotational speeds for PS material fatigue test specimens show that as the machine/specimen shaft rotational speed increases at S > 150 MPa, N almost coincides, but at S < 150 MPa, N decreases, which is shown by the S-N curve (see Fig. 9) which at the top of the curve lines almost coincide and at the bottom it is farther to the left at 2200 rpm than at 2000 rpm and 1800 rpm. Compared with the HIPS specimen in Fig. 8, at S < 70 MPa, the N value of the PS specimen was lower.

The condition of the LDPE specimens plus its 70% scrap before bending and after bending 180° without showing initial indications of cracking, means that the condition is very ductile, so it is a fatigue-resistant material that is difficult to test for fatigue, therefore fatigue testing cannot be carried out on LDPE specimens (see Fig. 10).

Fig. 10. LDPE (top) and LDPE + 70 % scrap (bottom) specimens before and after bending 180° without initial indication of cracking

The condition of the LDPE and LDPE specimens mixed with 70% scrap resulting from injection molding is not possible to test for fatigue, due to their very ductile or fatigue-resistant nature, in other words their fatigue life can be very long (see Fig. 11).

Fig. 11. LDPE and LDPE + 70 % scrap specimens resulting from injection molding

The fatigue test results show that the N at 2200 rpm speed testing in the range S 70 to 230 MPa for PP materials is about 15 $x10^5$ Cycles, HIPS is 18 $x10^4$ Cycles, ABS is 12 $x10^5$ Cycles, and PS materials is 16 $x10^4$ Cycles, and the LDPE specimen materials mixed with its 70% scrap cannot be tested for fatigue because they are very ductile or fatigue resistant.

The fatigue/endurance limit is the stress level below which the loading cycles in the fatigue test, an infinite number of cycles can be applied to a material without fatigue failure, especially for Iron alloys and Titanium alloys [26], but for aluminum, copper and other metals have not a fatigue limit, including polymers that are eventually damaged even though the amplitude of the stress applied to them is small. For the LDPE material mixed with 70% recycled material, it still has very ductile properties, which can fracture during the fatigue test, but requires a very long test time, in practice the material can be said to be fatigue resistant. In its application, if the polymer material has been used for a certain duration of time, natural degradation can occur resulting in the polymer material becoming less ductile or more brittle which allows its fatigue life to become shorter.

4 Conclusions

Conclusions that can be drawn from the discussion results for the shaft-machine/specimen rotational speed in the fatigue test at 2200 rpm in the bending stress range (S) of 70 to 230 MPa, include:

1) For PP materials at various levels of S, the tendency for fatigue life (N) to be shorter is obtained, as shown in the S-N curve (see Fig. 6) the more it is shifted to the left, it reaches around 15 $x10^5$ Cycles;
2) ABS material at $S > 110$ MPa, N slightly decreased, but at $S < 110$ MPa, N tended to be shorter as evidenced by the S-N curve (see Fig. 7) at the top of the curve almost coincides and at the bottom it is increasingly shifted to the left achieve is 12 $x10^5$ Cycles;
3) The HIPS material at $S > 150$ MPa, the N relatively slightly decreased, but at $S < 150$ MPa, N decreased quite a bit, which in the S-N curve (see Fig. 8) at the top of the curve line almost coincides and at the bottom it is increasingly at the left is up to 18 $x10^4$ Cycles;

4) The PS material shows that at S > 150 MPa, N almost coincides, but at S < 150 MPa, N decreases, which is shown by the S-N curve (see Fig. 9) where the curve lines almost coincide at the top and at the bottom getting to his left 16 $x10^4$ Cycles. Compared to the HIPS specimen (see Fig. 8), at S < 70 MPa, the N value of the PS specimen is lower; and
5) The LDPE specimen material with its 70% scrap mixture does not allow fatigue testing because it requires a very long test duration and is very ductile or fatigue resistant. LDPE and LDPE materials mixed with recycled materials which have very ductile properties are suggested in the future to be possible and very appropriate to be used as flexible shafts required by rotary rod fatigue testing machines working principle of R.R. Moore.

Acknowledgment

The authors would like to thank for financial support from the Center for Research and Community Service (*P3M*), State Polytechnic of Malang, Ministry of Education, Culture, Research and Technology of the Republic of Indonesia through contract Number 5590/PL2.1/HK/2023 for research on Plastic Specimen Fatigue Testing from Injection Molding Results.

References

1. Lu, Z., Feng, B., Loh, C.: Fatigue behaviour and mean stress effect of thermoplastic polymers and composites. Frattura ed Integrità Strutturale, vol. 46. pp. 150-157 (2018).
2. Handayani, S. U., Fahrudin, M., Mangestiyono, W., Fadlu, A. H. M.: Mechanical properties of commercial recycled polypropylene from plastic waste. J of Vocational Studies on Applied Research, vol. 3, no. 1, pp. 1-4 (2021).
3. Yilmaz, T., Sahin, T., Sinmazcelik, T.: Fracture characteristics of high impact polystyrene under impact fatigue loadings. J Mater Sci., vol. 44, pp. 4308-4314 (2009).
4. Aumnate, C., Rudolph, N., Sarmadi, M.: Recycling of polypropylene/polyethylene blends: effect of chain structure on the crystallization behaviors. Polymers, vol. 11, No. 1456, pp. 2-18 (2019).
5. Padzi, M. M., Bazin, M. M., Muhamad, W. M. W.: Fatigue characteristics of 3D printed acrylonitrile butadiene styrene (ABS). In: 4th AMMSE 2017 IOP Conf. Series: Materials Sci. and Engineering, IOP Publishing, Tianjin, China, 269, p. 012060 (2017).
6. Mura, A., Ricci, A., Canavese, G.: Investigation of fatigue behavior of ABS and PC-ABS polymers at different temperatures. Materials, vol. 11, no. 1818, pp. 1-14 (2018).
7. King, C. B., Hong, Y., DeHart, S. P., DeFeo, P. A., Pan, R.: Planning fatigue tests for polymer composites. Journal of Quality Technology, p. 1-33 (2016).
8. Shanmugam, V., Das, O., Babu, K., Marimuthu, U., Veerasimman, A., Johnson, D. J., Neisiany, R. E., Hedenqvist, M. S., Ramakrishna, S., Berto, F.: Fatigue behaviour of FDM-3D printed polymers, polymeric composites and architected cellular materials. Int. J of Fatigue, vol. 143, no. 106007, pp. 1-15 (2021).
9. Amraei, J., Katunin, A.: Recent advances in limiting fatigue damage accumulation induced by self-heating in polymer–matrix composites. Polymers, vol. 14, No. 5384, pp. 1-88, (2022).

10. Bakhtiari, H., Aamir, M., Rad, M.: Effect of 3D printing parameters on the fatigue properties of parts manufactured by fused filament fabrication: a review. Appl. Sci., vol. 13, no. 904, pp. 1-27 (2022).
11. Kuzmanovi, M., Delva, L., Cardon, L., Ragaert, K.: The effect of injection molding temperature on the morphology and mechanical properties of PP/PET blends and microfibrillar composites. Polymers, vol. 8, no. 355, pp. 1-16 (2016).
12. Korycki, A., Garnier, C., Irusta, S., Chabert, F.: Evaluation of fatigue life of recycled opaque PET from household milk bottle wastes. Polymers, vol. 14, no. 3466, pp. 1-16, (2022).
13. Haque, M. M. U., Goda, K., Ogoe, S., Sunaga, Y.: Fatigue analysis and fatigue reliability of polypropylene/wood flour composites. Advanced Industrial and Eng. Polymer Research, vol. 2, pp. 136-142 (2019).
14. Keller, J. H., Altstädt, V.: Influence of mid-stress on the dynamic fatigue of a light weight EPS bead foam. e-Polymers, vol. 19, pp. 349-354, (2019).
15. Xu, F., Zhao, Y., Li, K.: Using waste plastics as asphalt modifier: A Review. Materials, vol. 15, np. 110. pp. 1-26 (2021).
16. Estepa, J. A. R., Salcedo, E. V. G., Quintana, H. A. R., Lizcano, F. A. R., Martínez, J. G. B.: Mechanical behavior of low-density polyethylene waste modified hot mix asphalt. Sustainability, vol. 14, no. 4229, pp. 1-19 (2022).
17. Mohamadi, M. R., Mohandesi, J. A., Homayonifar, M.: Fatigue behavior of polypropylene fiber reinforced concrete under constant and variable amplitude loading. J of Composite Materials, vol. 47, no. 26, pp. 3331-3342 (2018).
18. You, Q., Miao, L., Li, C., Fang, H., Liang, X.: Study on the fatigue and durability behavior of structural expanded polysyrene concrete, materials, vol. 12, no. 2882, pp. 1-19, (2019).
19. Kanters, M. J.W., Douven, L. F. A., Savoyat, P.: Fatigue life prediction of injection moulded short glass fiber reinforced plastics, Procedia Structural Integrity 19, pp. 698-710 (2019).
20. Shreyas, P., Trishul, M. A., Kumar, R. C., Babu, K. R. K.: Testing of Al 7075 specimen using dual specimen rotating bending fatigue testing machine. Int. Advanced Research J. in Sci., Eng. and Tech., vol. 2, no. 4, pp. 11-13 (2015).
21. Comprehensive guide on polypropylene (PP). https://omnexus.specialchem.com/selection-guide/polypropylene-pp-plastic?gclid=Cj0KCQjwnf-kBhCnARIsAFlg493-Rr2JGPWNpHiuBOvKi-W4fGdD03UGy1ZUo6GSnGLiOR8x2SJqFzoaAqwIEALw_wcB last accessed 2023/06/22.
22. LDPE-low-density polyethelene-properties and uses. https://en.wikipedia.org/wiki/Low-density_polyethylene last accessed 2023/06/22.
23. Comprehensive guide on acrylonitrile butadiene styrene (ABS). https://omnexus.specialchem.com/selection-guide/acrylonitrile-butadiene-styrene-abs-plastic last accessed 2023/06/22.
24. High Impact Polystyrene (HIPS). https://polymerdatabase.com/Commercial%20Polymers/PS2.html last accessed 2023/06/22.
25. Polystyrene-density-strength-melting point-thermal conductivity. https://material-properties.org/polystyrene-density-strength-melting-point-thermal-conductivity/ last accessed 2023/06/22.
26. Alviano, D. K.: Injection molding standard fatigue test specimens ABS material and estimated fatigue life (Cetak Injeksi specimen uji lelah standar bahan abs and estimasi umur lelah). Bachelor Final Report, Mechanical Engineering Department, State Polytechnic of Malang, Indonesia (2021).

27. Fatigue limit, https://en.wikipedia.org/wiki/Fatigue_limit last accessed 2023/08/24.