

Experimental Investigation on the Effect of Thermal Ageing on Mechanical Characteristics of Polyamide12 Processed Using Selective Laser Sintering

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EXPERIMENTAL INVESTIGATION ON THE EFFECT OF THERMAL AGEING ON MECHANICAL CHARACTERISTICS OF POLYAMIDE12 PROCESSED USING SELECTIVE LASER SINTERING

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ABSTRACT

This study investigates the variation in mechanical characteristics of Polyamide-12 (PA-12) specimens on account of thermal ageing. PA-12 has high tensile strength, long life, high chemical resistance, and excellent electrical insulation elements for use in various industrial application including in automotive, aerospace and electronics etc. Test specimens of 150 numbers are fabricated using Selective Laser Sintering (SLS) and exposed to different temperatures and humidity levels. Pre and post structural examinations have been conducted to observe the variation in tensile, compressive, and flexural strength of the material due to thermal ageing. In addition, microstructural studies are done to understand the metallurgical changes in the materials which caused the property changes. Early ageing (1–3 weeks) caused the tensile strength to drop (23.10 to 11.40 MPa) due to chain scission and thermal degradation. Later (4–8 weeks), strength and modulus increased (up to 29.20 MPa and 387 MPa) due to post-crystallization and molecular rearrangement, indicating recovery and stabilization. Flexural strength and modulus increased significantly (32.35 MPa and 647.5 MPa after 8 weeks). Compression strength decreased initially from 68.46 MPa to 45.97 MPa, then recovered up to 67.65 MPa after 8 weeks. Compression modulus increased significantly from 288.25 MPa to 768.65 MPa, reflecting improved modulus with ageing. The effects are dependent on the time of thermal ageing (Environmental effects) and point towards thermal degradation of mechanical properties is observed in fabricated PA-12 upon thermal ageing. Therefore, environmental issues cannot be ignored when contemplating the design of parts produced by Selective Laser Sintering (SLS) printer.

Keywords: Polyamide -12; Selective laser sintering; Thermal Ageing; Mechanical properties; Morphology; Additive manufacturing.

1. Introduction

Additive Manufacturing (AM), commonly known as 3D printing, is a revolutionary process of creating objects by building them layer by layer using digital 3D models. Unlike traditional manufacturing methods such as machining, casting, or subtractive techniques, AM adds material rather than removing it. This approach results in more efficient material utilization and enables the creation of complex geometries that are difficult or impossible to achieve through traditional manufacturing methods. This flexibility makes additive manufacturing very versatile, leading to short times between order and delivery. It also lowers production costs, which is crucial in markets that frequently experience rapid shifts in demand [1], [2]. As a result, AM processes have found their way in variety of industrial sectors due to the need for custom parts, weight reduction and efficient use of materials [3]. The most common form of polymer AM technology adopted in industries is Selective Laser Sintering (SLS). This technique uses a focused laser beam to selectively sinter powdered materials like polyamide to create solid parts. The technique allows for manufacturing of robust and reliable parts with excellent mechanical characteristics. Therefore, SLS technique can be employed in aerospace, automotive and biomedical sectors. [4], [5], [32] [33]. Despite its advantages, long-term durability and ageing behavior remain critical challenges for SLS-printed materials [6]. Ageing is a natural process that affects materials over time due to environmental and operational conditions. It results in physical, chemical, and structural changes that influence the performance and stability of materials. Mechanical ageing in polymers occurs through various mechanisms such as thermal ageing, where exposure to high temperatures degrades structural integrity where prolonged humidity exposure leads to swelling, hydrolysis, and strength reduction[16]. Other factors include oxidative degradation, cyclic loading, chemical exposure, radiation and electrochemical ageing, all of which can impact material performance [7], [8], [31].

The study of thermal ageing in polymers has been ongoing since the 1960s. Thermal ageing was initially explored to predict degradation in polymers, while hydrothermal ageing gained prominence in sectors such as aerospace and automotive, where extreme environmental conditions significantly impact material performance [9]. Previous studies have shown that prolonged exposure to high temperatures and humidity can significantly affect the structural integrity of polyamide-based materials. For instance, investigated the long-term degradation of Polyamide 6.6 and found that hydrolytic and oxidative effects dominate at different temperature ranges, leading to substantial reductions in mechanical properties [10]. Likewise, laser-sintered parts filled with glass-reinforced polyamide PA-12, which have been aged

through temperature and humidity exposure, indicate considerable decreases in tensile strength and elongation at break [11]. Nevertheless, complete knowledge regarding how ageing affects the lifespan of SLS-printed PA-12 products has yet to be acquired. Although selective laser sintering technology is extensively used for polymer manufacturing processes, limited information exists regarding the effect of heat aging on PA-12 over a longer period of time. [11], [12].

This research study aims at examining the influence of thermal aging on the properties of SLS printed PA-12, studying the changes in melting behavior and crystallization behavior and gaining insight into the long-term durability of PA-12 for use in harsh environments. PA-12 specimens are subjected to thermal ageing at 50°C and 80°C. The effects of ageing were analysed for different durations (1, 2, 3, 4, 8) weeks by conducting tensile, flexural, and compression tests, along with Differential Scanning Calorimetry (DSC) and Scanning Electron Microscope (SEM) for morphological structure. The findings guide us for effective material selection and process optimization for SLS-printed components in high performance including aerospace industries applications.

2. Materials and Methods

2.1. Manufacturing of PA-12 specimens

Polyamide generally known as Nylon is a prominent polymer in Selective Laser Sintering (SLS) has commercial varieties such as Polyamide 6, Polyamide 11, Polyamide 12, Polyamide 66, etc [18], [30], [31]. PA-12 is frequently used in SLS and maintains the highest market value among polymers.

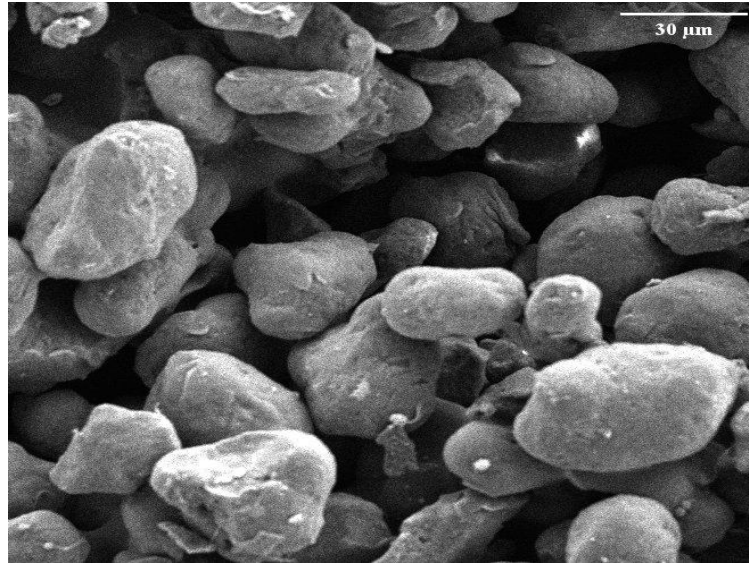


Figure 1. SEM image of new PA12 powder

The polymeric powder material used in this study was the commercially available black coloured PA-12 (SP301 Black) supplied by M/s Guangdong Silver AM Technology Co., Ltd, China, with an average particle size of 45–60 μm , density of 0.63 g/cm^3 , melting temperature of 185°C and melt flow rate of 40 g/10 min respectively shown in the Figure 1. Dimensions and geometry of the test specimens for carrying out tensile, Flexural and compression strengths are depicted in Figure 2.

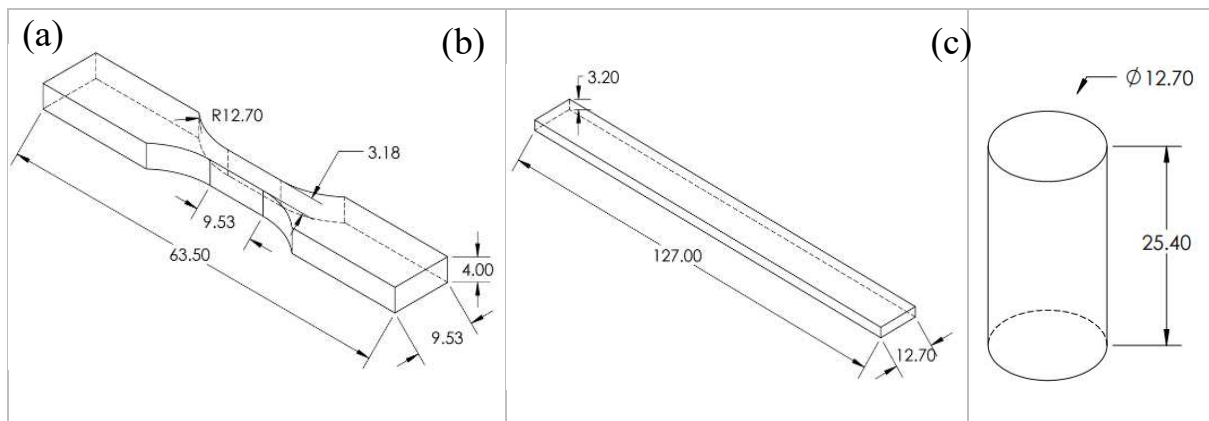


Figure 2. ASTM Standard Test specimens (a) Tensile (b) Flexural (c) Compression (All dimensions are in mm)

The specimens were fabricated using an Fabforge make SLS 3D printer which has a chamber volume of $100 \times 100 \times 100$ mm (shown in Figure 3). The fabricated specimens for conducting flexural (ASTM D790-15), tensile (ASTM D638 Type V) and compression tests (ASTM E9-19) [29], are shown in Figures a, b and c respectively.

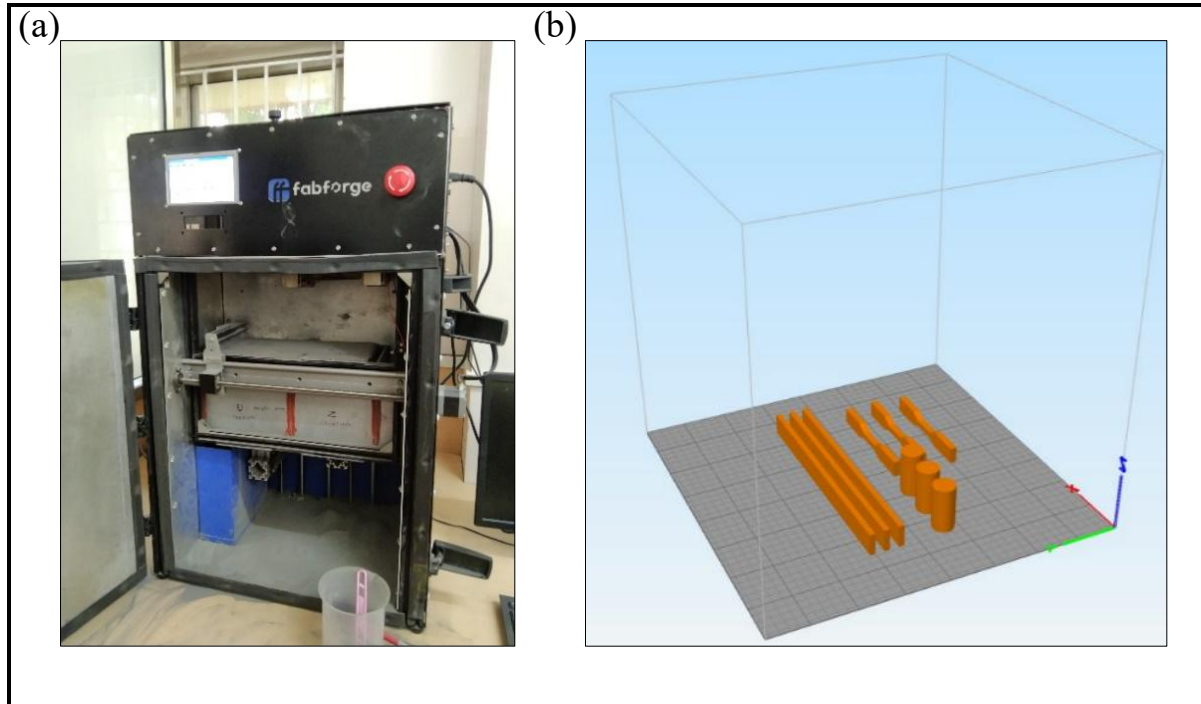


Figure 3. Pre-fabrication: (a) SLS printer (b) Orientation of build samples

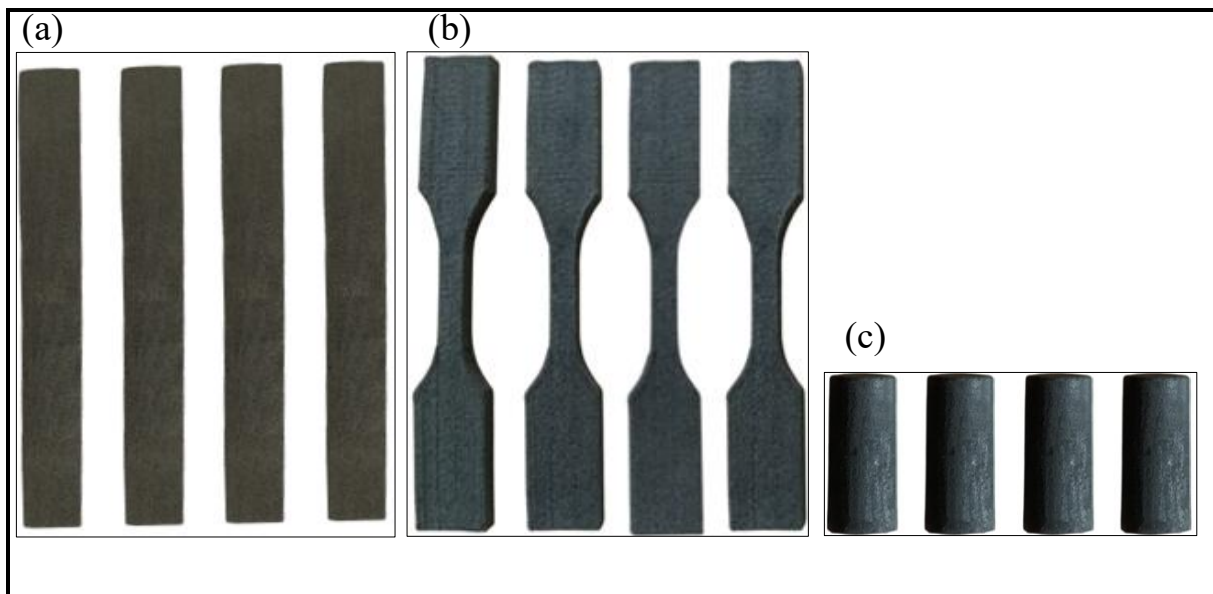


Figure 4. SLS printed specimens: (a) Flexural (b) Tensile (c) Compression

2.2. Mechanical Testing and Thermal Ageing

Tensile, Compression and Flexural tests are carried out in accordance with the ASTM standards D638, D790 and D695 respectively using a Tinius Olsen H25 KT machine. The changes in the

mechanical characteristics of aged and unaged specimens are predicted. The tensile, flexural and compression tests are carried out at a speed rate of 1 mm/min, 2 mm/min and 1 mm/min respectively.

The SLS printed PA-12 samples are subjected to thermal ageing in the M/s CME make environmental chamber (shown in the Figure 5) according to the ISO 188 [28].



Figure 5. Environment chamber used for ageing studies

The chamber was used for ageing under controlled thermal conditions for different ageing periods as tabulated in the Table 1.

Table 1. Thermal ageing cycles

S. No.	Ageing Temperature, (°C)	Ageing Time (weeks)
1	50	1
2		2
3		3
4		4
5		8 (Accelerated) (1.83 hours @105°C)
6	80	1
7		2
9		3
10		4
11		8 (Accelerated) (86.84 hours @105°C)

The chamber was programmed for four weeks and specimens were removed from the chamber every week as per the requirement. A minimum of five specimens were tested for each ageing time to ensure repeatability of the measurements. In total, 165 specimens were used—55 each for tensile, flexural, and compression tests. Ageing for 8 weeks is performed as per the accelerated ageing procedure which helps in predicting the effects of prolonged thermal exposure at lower temperatures in short period of time [13], [14]. Enhancing the precision of lifetime predictions for polymer materials and activation energy can be achieved through the application of the time-temperature superposition method. This method assumes that the characteristic changes induced by higher temperatures over a shorter duration are equivalent to those occurring over extended periods under normal conditions [13]. Normal ageing was conducted at 50°C and 80°C for 8 weeks. The relationship between accelerated ageing and actual conditions described using this equation (1) and (2):

$$a_T = \exp \left[\frac{E_a}{R} \left(\frac{1}{T_{\text{actual}}} - \frac{1}{T_{\text{accelerated}}} \right) \right] \quad (1)$$

where $T_{\text{accelerated}}$ is an accelerated temperature (K), T_{actual} is an actual temperature (K), E_a is an activation Energy is 122,000 J/mol, R is a Gas constant is 8.314 J/mol·K [23].

$$t_{\text{accelerated}} = \frac{t_{\text{actual}}}{a_T} \quad (2)$$

where a_T is a shift factor no units, t_{actual} is an actual ageing time which is 1344 hours, $t_{\text{accelerated}}$ is an accelerated ageing time is hours.

2.3. Metallurgical Analysis

Microstructure analysis was performed using a ZEISS make Gemini 300 SEM. The Scanning Electron Microscope (SEM) test examines the surface morphological structure of both aged and unaged samples after mechanical testing. SEM micrographs were obtained at 150X and 300X magnification with an acceleration voltage at 10 kV. The most representative images were selected from five specimens and presented.

Differential Scanning Calorimetry (DSC) test is carried out to identify the changes in the crystallinity and thermal properties using a Mettler Toledo make DSC 822e. PA-12 powder mass each of 3 mg was scanned in nitrogen atmosphere at a heating rate of 10 °C/ min. DSC expression curves were taken by heating the samples in the temperature range from - 100 to 300 °C. SEM analysis was conducted to investigate the morphological changes in PA-12 powder and thermally aged, sintered parts under different mechanical loading conditions. The

unprocessed PA-12 powder shows large spherical, smooth particles, which are ideal for SLS due to their excellent flowability and packing behavior.

3. Mechanical Testing

3.1. Tensile test

In order to determine the effect of thermal ageing on the mechanical performance of PA-12 parts and in addition to change their aesthetic and chemical properties, tensile testing was conducted. This work demonstrates on how the printed parts behave under tensile load with samples exposed up-to 4 weeks of thermal ageing under 50°C and 80°C. 8 weeks of thermal ageing is carried out as Accelerated test as discussed in the previous section. The results of tensile tests are illustrated in Figure 6 and are presented in Table 2.

At 50°C under thermal ageing for 1 week, Ultimate Tensile Strength (UTS) decreases to 19.7 MPa from 23.1 MPa but later it recovers to 26.7 MPa after 4 weeks due to molecular rearrangement, crosslinking and secondary crystallization initially strengthens behaviour [19]. In contrast, 80°C thermal ageing causes decrement of Ultimate Tensile Strength (UTS) to 11.4 MPa in 1 week with partial recovery 23 MPa at 4th week that results in greater embrittlement due to faster oxidation and chain scission and therefore material behave predominantly in a brittle manner. Accelerated thermal ageing with UTS decreasing from 31.46 MPa to 29.2 MPa at 50 °C and to 29.16 MPa at 80 °C after 8 weeks, confirm that the higher temperatures increase degradation rates.

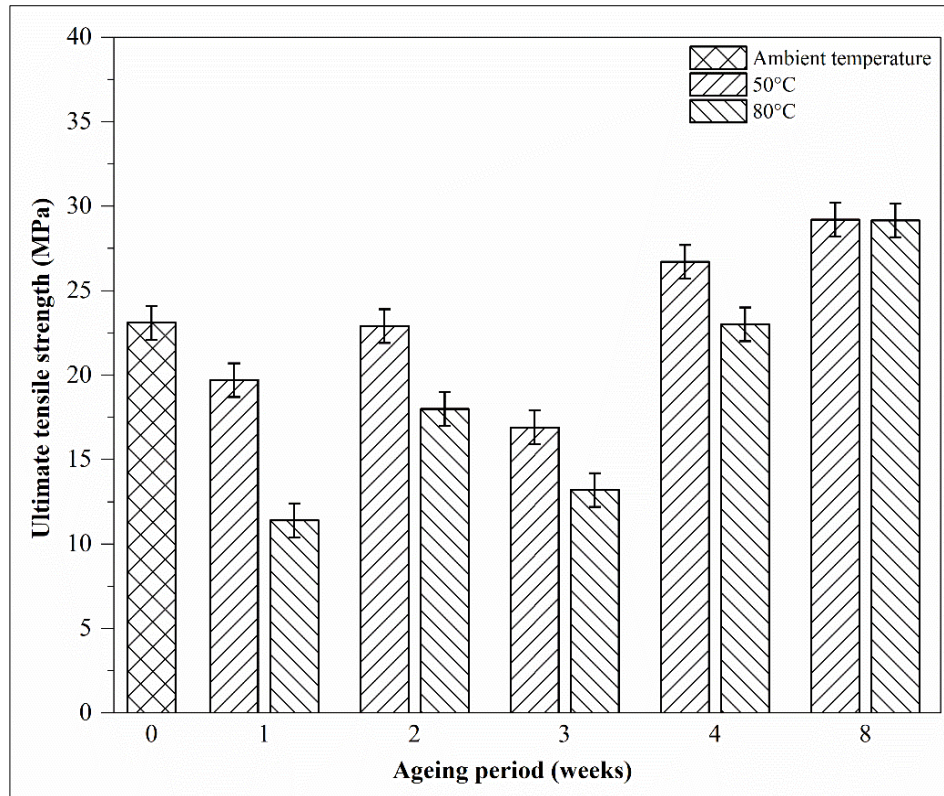


Figure 6. Effect of ageing on the ultimate tensile strength

Similarly, in Figure 7, at 50°C, elongation decreased from 12.7% to 8.57% at 3rd week but recovers to 12.7% at 4th week, indicating structural recovery. However, at 80 °C, elongation drops significantly from 12.7% to 7.76% in the 1st week itself showing rapid stiffening. Elongation trends indicate severe embrittlement (The observed elongation reduction from 21.8% to 14.4% at 80 °C clearly indicates severe embrittlement), which can be explained by the rapid oxidation and chain scission in the polymer matrix at higher temperatures. Specifically, thermal oxidation at elevated temperatures breaks molecular chains, decreasing the average molecular weight and disrupting hydrogen bonding between PA-12 chains. This leads to a more fragile structure that has less plastic deformation capability, and this directly affects the elongation of the materials during tensile testing. From the SEM images obtained from such embrittled structures, the surface appears as smooth surfaces without the characteristic fibrillar structures in ductile tearing (as indicated by the mechanical test results). This is especially true for the sample tested at 80 °C, wherein the elongation dropped from 21.8% to 14.4 %.

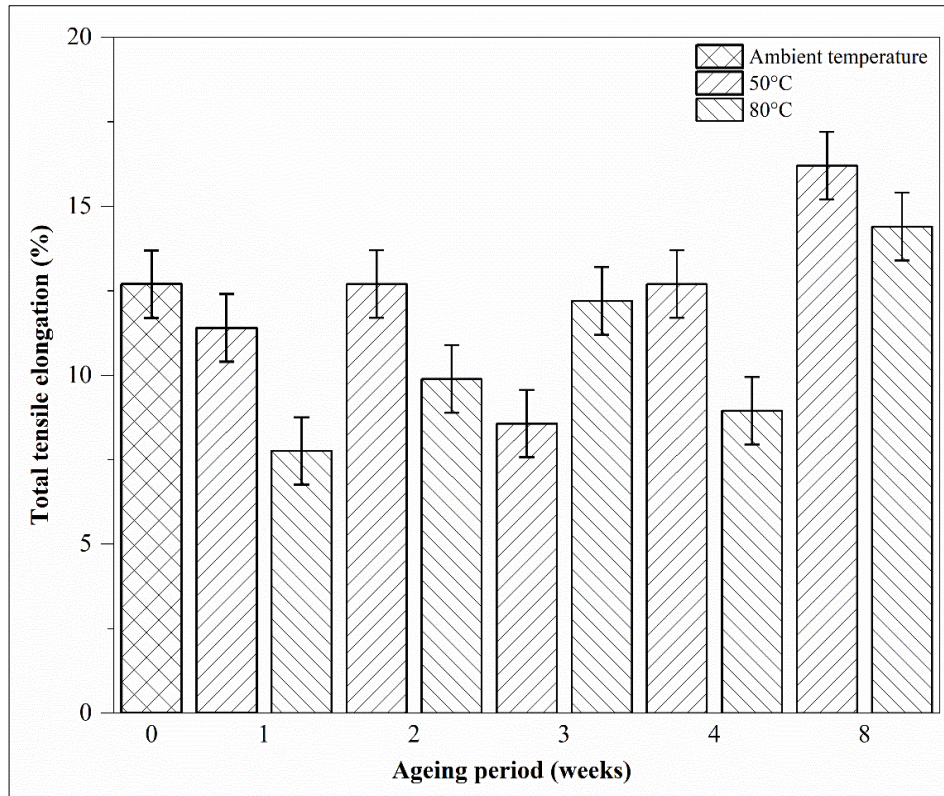


Figure 7. Effect of ageing on the tensile elongation

Figure 8 presents the Young's modulus of PA-12 before and after 8 weeks of thermal aging at temperatures of 50°C and 80°C. It can be seen from the data that there is a slow drop in stiffness; thus, the modulus drops from 399.60 MPa (untreated sample) to 387.34 MPa (-3.1%) and 385.65 MPa (-3.5%) at 50°C and 80°C, respectively. This indicates that, although thermal aging leads to molecular reorganization and post-crystallization in the early stages, long-term thermal aging induces degradation reactions like oxidation and chain scission, resulting in lower modulus.

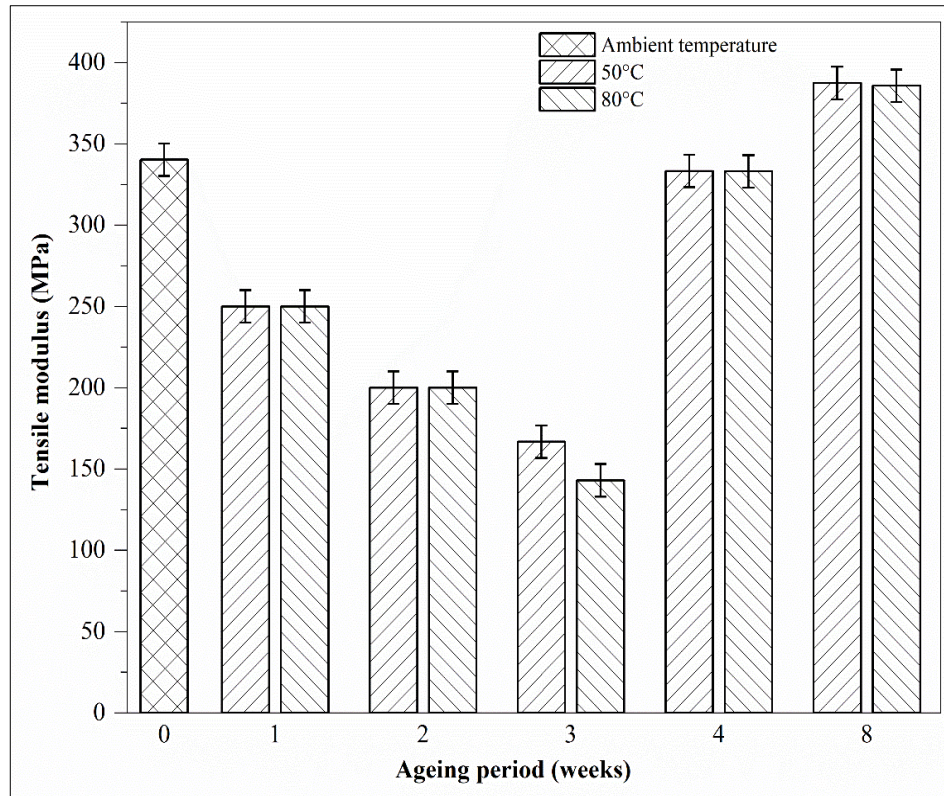


Figure 8. Effect of ageing on the tensile modulus

Table 2. Test Results

Ageing Temperature (°C)	Ageing Time (week)	Ultimate Strength (MPa)	Total Elongation (%)	Tensile Modulus (MPa)
Ambient Temp.	0	23.10	12.70	340.21
50	1	19.70	11.40	250.00
50	2	22.90	12.70	200.00
50	3	16.90	8.57	166.70
50	4	26.70	12.70	333.30
50	8	29.20	16.20	387.34
80	1	11.40	7.76	250.00
80	2	18.00	9.89	200.00
80	3	13.20	12.20	143.00
80	4	23.00	8.95	333.00
80	8	29.17	14.40	385.66

The tensile-aged sample has a fibril appearance due to the formation of fibers because of the molecular stretching. This indicates that aging does not completely eliminate the tendency towards ductility since it still undergoes plastic deformation when subjected to tensile forces.

Low strength and elongation (degraded PA12) correspond to the brittle type (smooth surface; few fibrils), whereas high strength and elongation (post-aged PA12) correspond to the ductile type (crazed; fibrillated surface). The presence of voids (due to crazing network) observed in the SEM analysis confirms the ductile fracture of the sample with the highest elongation as illustrated in Figure 9. In summary, the results obtained from the SEM fractography confirm the trend of the tensile test wherein aging causes embrittlement (flat and smooth fracture surface) that explains the decrease in UTS and elongation values at the beginning.

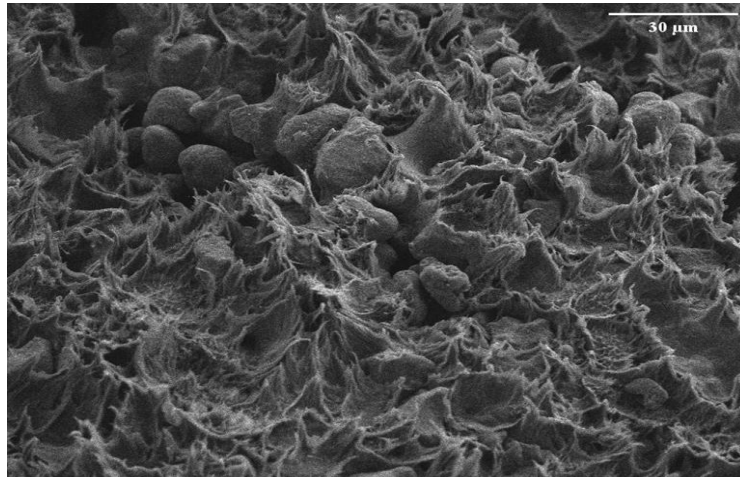


Figure 9. Fractography image of tensile part

3.2. Flexural test

From the outcomes of the flexural test conducted on specimens made from thermally aged PA-12 using Selective Laser Sintering (SLS), it is apparent that there are substantial differences in mechanical behavior depending on ageing conditions. From Table 3, it is seen that, at room temperature (unaged), the specimens had ultimate strength of 18.30 MPa, elongation of 11.10%, and Young's modulus of 377.00 MPa [19]. These findings are used as a benchmark for assessing the impact of thermal aging [12]. At 50°C, the ultimate strength reduced from 18.30 MPa to 15.70 MPa in one week, while in two weeks, it declined to 14.80 MPa. The value of UTS in Figure 10 rose to 32.35 MPa in an unexpected manner in the eighth week. This could possibly be explained by post-crystallization or structure restructuring [20], [21]. There was a marginal rise in elongation during the initial period (12.90% in 2nd week), but there was a significant fall of elongation to 8.10% in the fourth week, indicating the embrittlement as a result of chain scissions [15]. The Young's modulus fluctuated, peaking at 647.50 MPa in 8th week, likely due to increased crystallinity [17].

At 80 °C, on the other hand, the ultimate strength was more inconsistent, varying from 14.10 MPa in the first week to 17.30 MPa in the third week, before rising significantly to 27.03 MPa in the eighth week. Such a non-linear trend is consistent with findings that have pointed out the competition between the oxidative and cross-linking processes at higher temperatures [22]. In Figure 11, the elongation reached a maximum of 14.60% in the first week before stabilizing at 11-14%, respectively[24]. As can be seen in Figure 12, Young's modulus exhibited the same variations, with values recorded at 485.67 MPa for 8th weeks, similar to the effects of aging that result in the hardening of PA-12 [25]. With respect to the above trends, the most important parameters for PA-12 aging are the aging temperature and time. The abrupt rise in strength at longer times (i.e., 32.35 MPa at 50°C/week 8) could be due to secondary crystallization[26].

The 8th week values obtained at both temperatures should be investigated using DSC to determine the underlying microstructural changes [6]. Ageing by thermal treatment can affect the flexural behavior of PA-12 depending on time and temperature, resulting in either degradation or improvement in its structure. This knowledge is crucial for practical purposes where durability is critical, such as in automotive and aerospace industries [27].

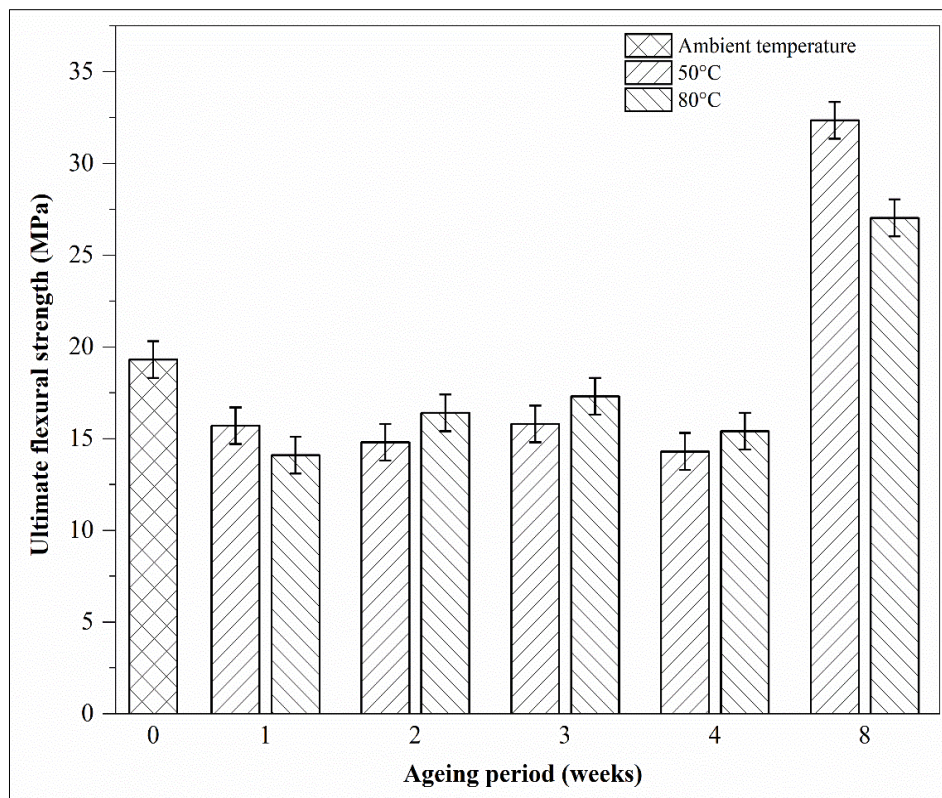


Figure 10. Effect of ageing on the ultimate flexural strength

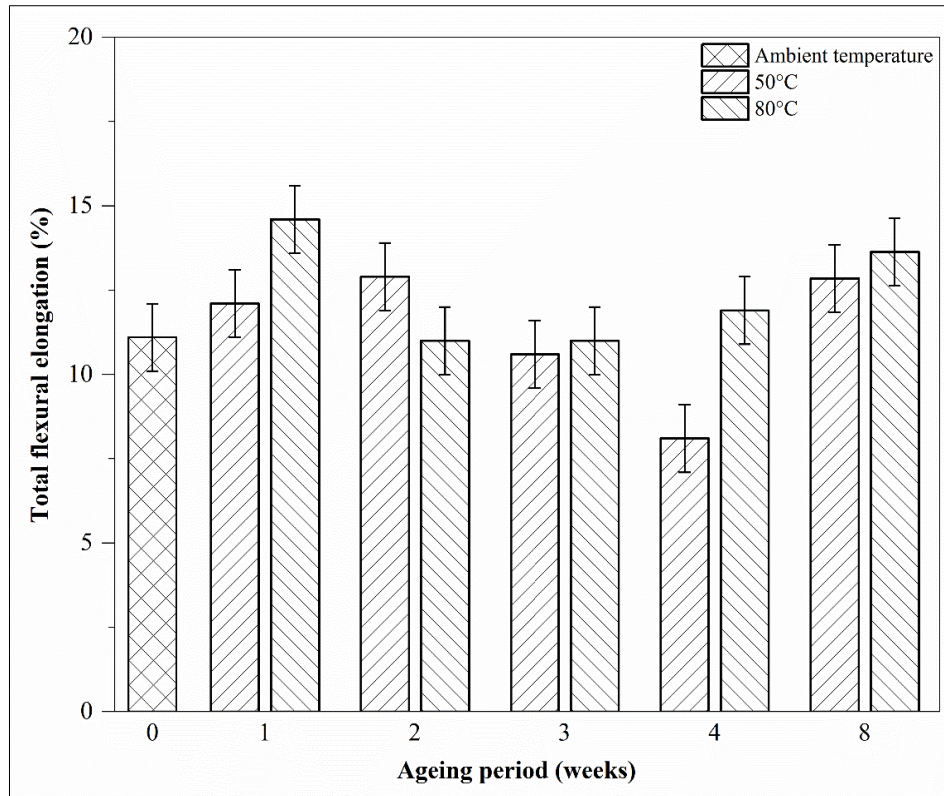


Figure 11. Effect of ageing on the flexural elongation

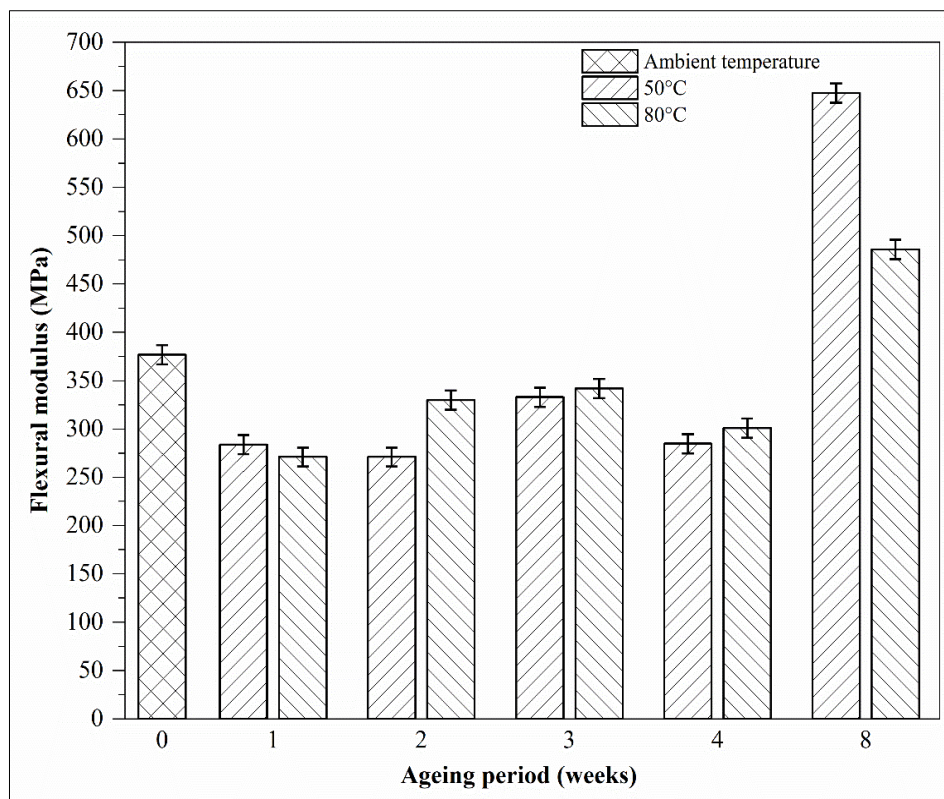


Figure 12. Effect of ageing on the flexural modulus

Table 3. Results of flexural test

Ageing Temperature (°C)	Ageing Time (week)	Ultimate Strength (MPa)	Total Elongation (%)	Flexural modulus (MPa)
Ambient temperature	0	18.30	11.10	377.00
50	1	15.70	12.10	284.00
50	2	14.80	12.90	271.00
50	3	15.80	10.60	333.00
50	4	14.30	8.10	285.00
50	8	32.35	12.85	647.50
80	1	14.10	14.60	271.00
80	2	16.40	11.00	330.00
80	3	17.30	11.00	342.00
80	4	15.40	11.90	301.00
80	8	27.03	13.63	485.67

The SEM picture in Figure 13 of the flexural sample displays a more condensed microstructure than the unaged or moderately aged samples. Surface morphology indicates densification, fewer micro-voids, and uniformity in spherulitic domains, implying that the phenomenon is associated with thermal annealing and secondary crystallization [28]. These changes usually result in higher crystallinity levels, increasing stiffness and load-carrying ability in thermoplastic materials such as PA-12. The phenomena are different from the conventional oxidation degradation, which involves surface cracking and void formation. The present study highlights a structural change involving the realignment of molecules into more stable lamellae through thermal ageing, particularly when moderate ageing temperatures (50–80 °C) are used [30]. The transformation decreases the free volume of the amorphous phase, improving inter-molecular interaction and leading to higher flexural strength [31]. There are similar reports on mechanical property improvements attributed to thermal-induced crystallization in selectively laser-sintered PA-12 samples subjected to thermal ageing [32]. Thus, the SEM evidence of structural consolidation supports the experimentally observed strengthening behavior after thermal ageing.

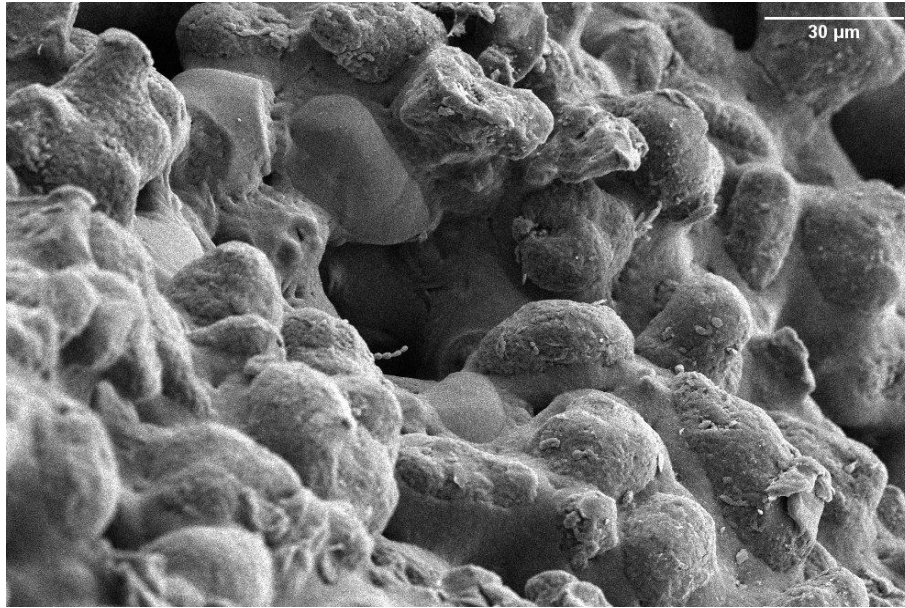


Figure 13. SEM analysis of flexural part

3.3. Compression test

From Table 4, it can be seen that the ultimate compressive strength and compression modulus of un-aged samples were 68.46 MPa and 288.25 MPa, respectively [19]. When exposed to 50 °C thermal ageing, the ultimate compressive strength of PA-12 samples remained relatively stable within the range of 58.62 to 61.28 MPa during weeks 1 to 4, after which there was a rebound to 66.16 MPa at week 8. The trend is shown in Figure 14, which depicts the evolution of ultimate compression strength with time during the thermal ageing process. The compression modulus of samples aged at 50 °C increased consistently, from 240.51 MPa at week 1 to 768.65 MPa at week 8. It is possible that the increased stiffness might be caused by post-crystallization or physical ageing processes [12]. The effect of ageing on compression modulus is clearly presented in Figure 15.

The results obtained at 80 °C showed higher variations, with the strength varying between 45.97–67.65 MPa and the compressive modulus varying between 480.48 and 660.42 MPa. While at week 8 the specimen strength has reached its original value of 67.65 MPa, similar to that of un-aged samples, there is a considerable reduction in strength at weeks 2 and 4 (45.97–46.64 MPa), suggesting opposing mechanisms [22]. The behavior of the compressive modulus was also relatively high at 80 °C (480.48–660.42 MPa), which may reflect thermally induced structural densification or transient molecular rearrangement [21].

The results obtained for the compression tests vary greatly from flexure tests, whereby strength tends to decrease with age. The stiffening seen in compression tests, especially at high

temperatures, implies that there may be an increase in the load carrying capacity of PA-12 during thermal aging [17]. At 768.65 MPa at 50 °C/week 8, the results show a 2.7 times increase in the material over aged samples. This is very useful for engineering purposes [28], but oxidation seems to play a role at 80 °C, especially weeks 2 and 4 [15]. The results obtained through the compression tests are complementary to those obtained through the flexure tests, showing how PA-12 reacts differently in terms of mechanical properties depending on the type of loading applied during thermal aging. While in the case of flexure, a decrease in strength was seen without much restoration, in compression, a significant increase in stiffness was recorded. These results imply that the process of thermal aging is largely affected by the state of stress [25]. Future studies should investigate microstructural evolution under these conditions to explain the observed mechanical changes [12].

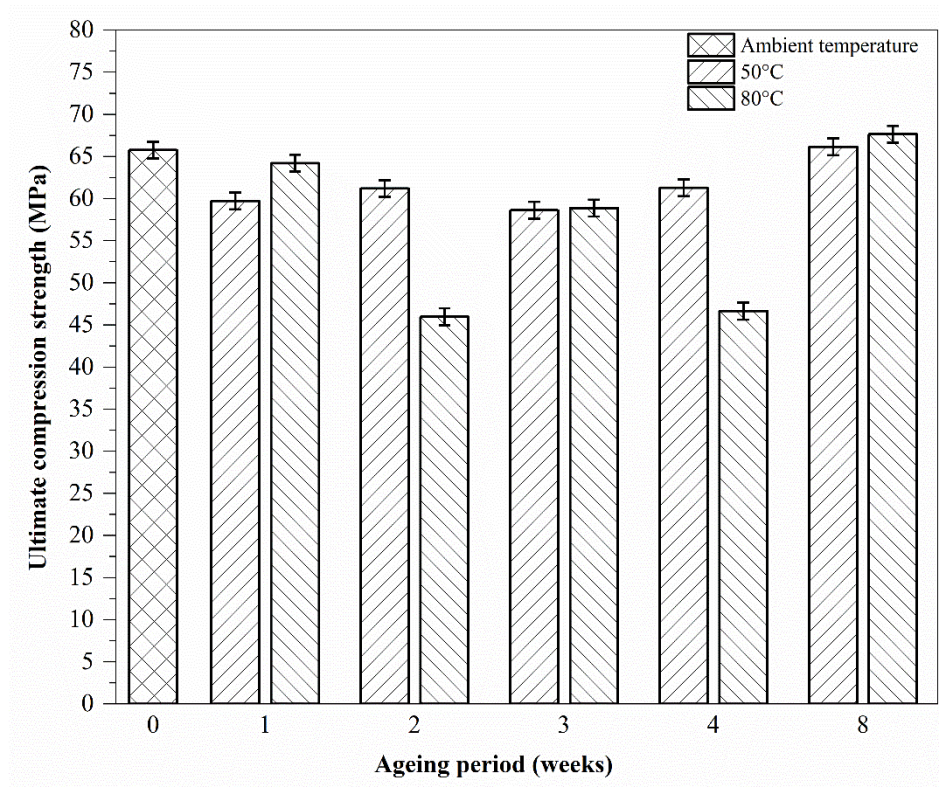


Figure 14. Effect of ageing on the ultimate compression strength

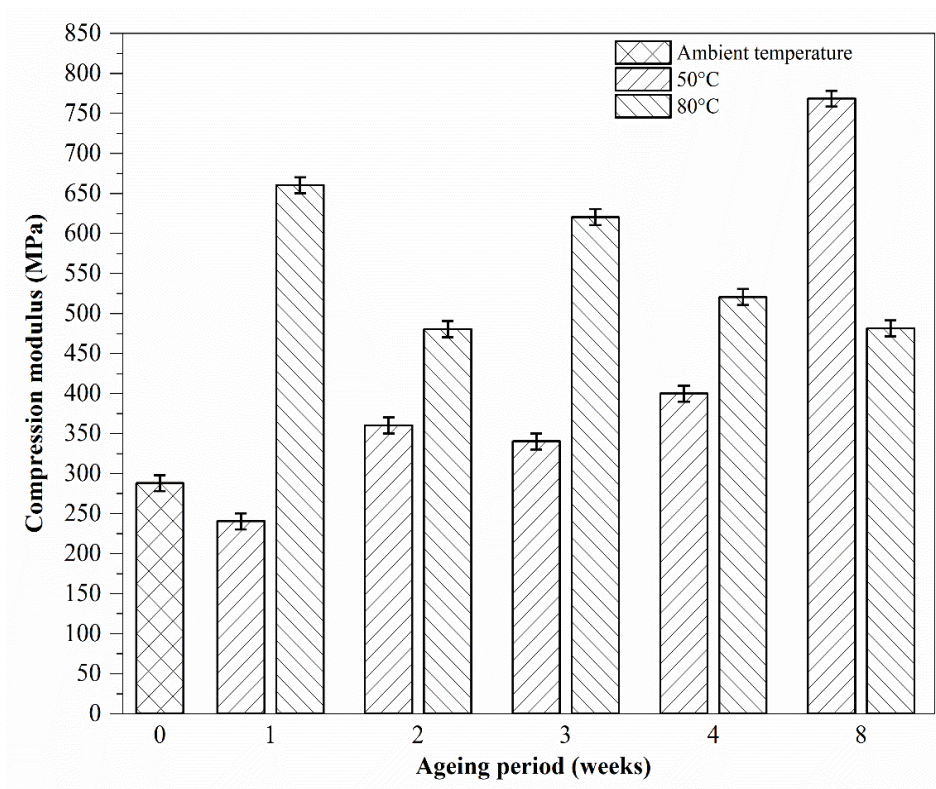


Figure 15. Effect of ageing on the compression modulus

Table 4. Results of compression test

Ageing Temperature (°C)	Ageing Time (week)	Ultimate Strength (MPa)	Compression Modulus (MPa)
Ambient temperature	0	68.46	288.25
50	1	59.72	240.51
50	2	61.2	360.36
50	3	58.62	340.45
50	4	61.28	400.19
50	8	66.16	768.65
80	1	64.21	660.42
80	2	45.97	480.48
80	3	58.88	620.65
80	4	46.64	520.75
80	8	67.65	481.64

4. DSC analysis of tensile test after ageing

The DSC profile in the first heating scan presented in Figure 16 shows a glass transition temperature (T_g) between 65–75 °C, representing the starting point where molecular motion occurs. This temperature is near to the thermal ageing temperature (50 °C), implying a possible occurrence of some chain rearrangements. As seen from Table 5, the melting temperature (T_m)

did not change much; it varied from 177.52 °C to 178.72 °C within a period of four weeks of thermal ageing. This negligible difference means that the crystalline structure of PA-12 is not affected by long-term thermal ageing below the melting point. Figure 17 illustrates slight variations in the T_c value at about 154 °C. The findings reported here are consistent with literature reports on PA-12 being a semi-crystalline thermoplastic with good thermal resistance properties [1]. Enthalpies were not constant but varied. The enthalpy of melting rose dramatically from 33.96 J/g in week 1 to 55.20 J/g in week 2 and then decreased before increasing again in the ensuing weeks. The same trend was noted in the enthalpy of crystallization. This indicates that recrystallization could occur, whereby heating at a temperature close to T_g gives room for mobility and restructuring of chains. This is typical of aged polymers, in which partial restructuring results in an increase in crystallinity [2].

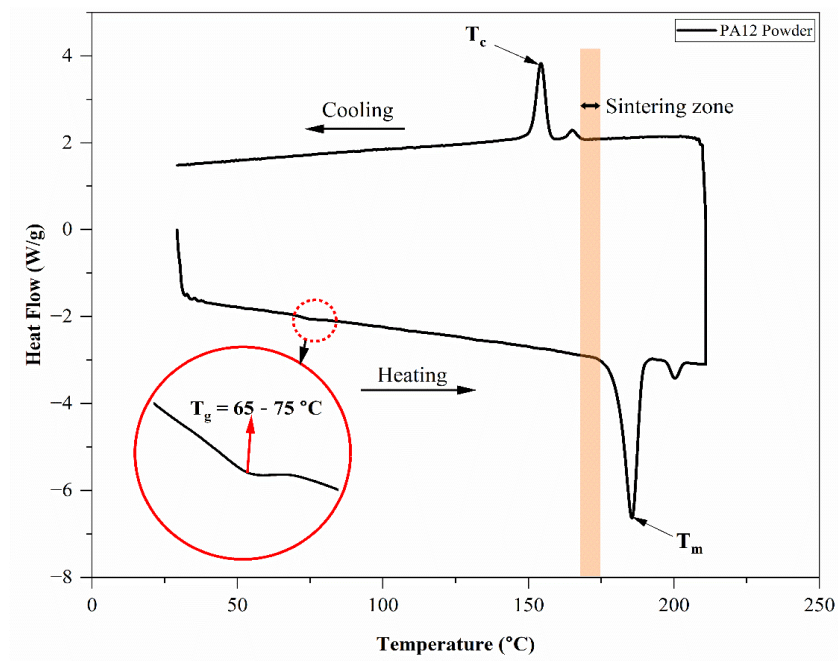


Figure 16. DSC of PA-12 Powder

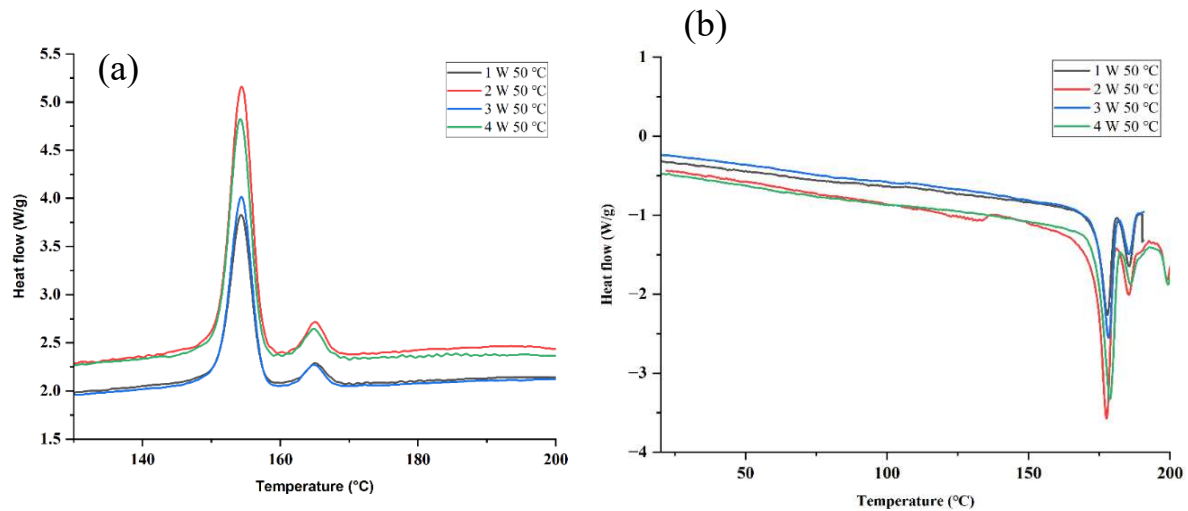


Figure 17. DSC test of aged tensile specimens: (a) Crystallization points and (b) Melting point of PA-12 Parts

Table 5. DSC of aged parts

S. No	Properties	1 Week 50°C	2 Week 50°C	3 Week 50°C	4 Week 50°C
1	Melting Point, T_m (°C)	177.85	177.52	178.34	178.72
2	Crystallization Point, T_c (°C)	154.31	154.41	154.35	154.21
3	Melting Enthalpy, ΔH_m (J/g)	33.96	55.2	37.53	44.08
4	Crystallization enthalpy, ΔH_c (J/g)	32.16	51.16	35.58	43.79

5. Conclusion

This study offered a detailed analysis of the ageing process for PA-12 specimens created by SLS technology, focusing on their mechanical properties, thermal stability, and microstructural changes. By conducting thermal aging experiments at 50 °C and 80 °C for different periods, important information about the longevity and strength of SLS printed PA-12 in harsh conditions was achieved. It can be concluded that elevated temperature exposure causes degradation in PA-12's mechanical properties as a result of the oxidation process, chain breakage, and decreased inter-layer adhesion. However, the longer periods of ageing at relatively moderate temperatures exhibited properties of material regeneration, which could have resulted from secondary crystallization, cross-linking, and chain realignment within the polymer. Further evidence was also found through the flexural and compression tests that the effects of aging differed depending on the loading mode, since compression samples displayed improved ductility after longer periods of ageing. The findings from the SEM, DSC, and EDS analyses further corroborated the mechanical results by showing the presence of degradation

in the material morphology, changes in thermal properties, and chemical alterations such as oxygenation and the presence of other elements, suggesting oxidative degradation and contamination of the material surface.

Further research may be focused on determining the effects of cyclical thermal aging to achieve an accurate simulation of realistic application conditions. Studies on the contribution of additive, filler, or coating use to increase thermal resistance and aging resistance may also add to the knowledge base. Furthermore, fatigue, impact strength, and environmental stress cracking testing of the material should be done in order to understand its durability for various applications in different sectors, including aviation, automotive, and medical.

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The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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This study did not involve human participants or animals, and hence ethical approval was not required.

Consent for publication

All others agree to publish the content of the manuscript.

Competing interests

The authors declare no competing interests.