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Araştırma Makalesi / Research Article

The Tensile Properties of Functionally Graded Materials in MSLA 3D Printing as a Function of Exposure Time

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ABSTRACT: Functionally graded additive manufacturing (FGAM) emerged from the combination of Functionally Graded Materials into additive manufacturing. This work involved the production of FGAM specimens to alter the characteristics of both the outer and inner zones of tensile specimens. This was achieved by adjusting the exposure time without additional costs or equipment. During the assessment, the tensile specimen was separated into three zones. The exterior layers were initially created with a 3-second exposure time, followed by the interior layers with a 15-second exposure time. Then, the process was reversed, with the outer layers exposed for 15 seconds and the inner layers exposed for 3 seconds. Subsequently, all layers were generated using exposure durations of 3 seconds and 15 seconds, respectively, without any alterations, resulting in a total of 4 distinct samples. The hardness and tensile tests were conducted on all specimens, both with and without post-curing, in order to assess the impact of post-curing. The outcomes indicate that the levels of hardness and maximum tensile strength rise as the final curing process progresses, but the elongation capability diminishes. The highest ultimate tensile strength, achieved after 15 seconds of exposure time with post cure, was measured at 46.46 ± 0.9 MPa. The green FGAM specimens have a greater ultimate tensile strength (35.85 ± 0.4 MPa) when created with an exposure time of 15-3-15 s. However, the specimen produced with an exposure time of 3-15-3 s demonstrates a higher ultimate tensile strength (38.77 ± 0.7 MPa) following post curing.

Keywords: MSLA printer, 3D printing, functionally graded material, additive manufacturing.

1. INTRODUCTION

Functionally Graded Materials (FGMs) are a specific category of composite materials that are particularly suitable for situations when one component must contain conflicting characteristics. FGMs are a category of substances distinguished by the existence of property fluctuations across their entirety (Hisham et al., 2022). The quick fabrication of 3D parts for diverse purposes has led to

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increased interest in additive manufacturing (AM) (Bayraklilar et al., 2023; Güdür et al., 2023; Kaya et al., 2023). Additive manufacturing (AM) has revolutionized modern manufacturing by enabling the creation of complex and customized structures (Demir et al., n.d.; Güdür et al., 2023). FGMs have attracted significant interest in the field of additive manufacturing (AM) due to their potential to provide tailored material properties within a single component (Loh et al., 2018; Ren et al., 2018). The advantages of AM techniques, including the capacity to fabricate intricate things, the minimal generation of waste, the low energy consumption, and the flexibility in design, render them highly appealing for the production of functionally graded materials (FGMs), heterogeneous multi-materials, as well as homogenous single-materials (Bazyar et al., 2023). The capability of AM to manufacture FGMs has been demonstrated, enabling the production of parts with discrete or continuous variations in their attributes and compositions throughout their volume (Nohut and Schwentenwein, 2022; Schneck et al., 2021). Briefly, functionally graded additive manufacturing (FGAM) is the process of deliberately altering the material arrangement within a component in order to produce a certain function (Hisham et al., 2022). This technology offers the potential for novel industrial applications and has been applied in various fields such as orthopedics, automobile, energy, aerospace, ceramics, and dentistry (Alshaikh et al., 2022; Bazyar et al., 2023; González et al., 2019; Rouf et al., 2022). Furthermore, the use of FGMs in AM has extended to the development of composite materials with heterogeneous microstructures, allowing specific physical and mechanical properties to change continuously in the thickness direction (Torabian and Khalili, 2020). This capability has opened up opportunities for the design and production of components with tailored performance characteristics, such as enhanced mechanical properties and improved functionality (Carraturo et al., 2019; Clarke-Hicks et al., 2022). The research on FGMs and AM has also delved into the mechanical performance and properties of additively manufactured materials. Studies have investigated the strength, cyclic properties, and impact toughness of additively manufactured components, providing insights into their structural integrity and suitability for various applications (Chmelko et al., 2023; Lucon and Hrabe, 2018). Additionally, the development of FGMs has led to the exploration of new materials, such as continuous fiber-reinforced thermosetting polymer composites, which offer high-performance characteristics and mechanical compatibility with specific applications (Rahman et al., 2023; Yao et al., 2019). The integration of FGMs with AM processes, particularly in the context of Stereolithography (SLA) grey resin, presents a promising avenue for the production of parts with customized material properties. In this context, the exposure time during the additive manufacturing process plays a critical role in influencing the material characteristics and attributes of the finished component. The photocuring conversion rate is dependent upon the exposure duration and exerts a substantial impact on material properties, including density, shrinkage, and elastic modulus (Bonada et al., 2017). SLA 3D printing involves the laser scanning and curing of the photopolymer resin point by point, while in DLP systems, UV light can cure an entire layer of the resin at once (Xiao et al., 2019). Additionally, there are many studies in the literature considering exposure time as a parameter to optimize the SLA printed parts (Borra and Neigapula, 2022; Seprianto et al., 2020; Temiz, 2023). The final characteristics of 3D printed materials are dependent upon the configuration and potential fluctuations of all manufacturing factors (Riccio et al., 2021). In summary, the integration of functionally graded materials with additive manufacturing processes, particularly in the context of SLA grey resin, presents a promising avenue for the production of parts with tailored material properties. The exposure time during the additive manufacturing process, along with the ability to achieve gradationally varying material organization, offers opportunities for the development of components with enhanced performance and functionality.

This investigation involved the production of FGAM dog bone tensile samples by controlling the exposure time using a Masked Stereolithography (MSLA). FGAM was created employing two distinct exposure times and samples without FGAM were likewise generated and analyzed under these exposure times. All dog bone tensile test specimens were created using the ASTM D638 standard test protocol (Anonymous, 2022) for evaluating the tensile characteristics of polymers.

2. MATERIALS AND METHODS

2.1 Material

This study utilized an Anycubic Photon M3 MSLA machine equipped with a light-source emitting at a wavelength of 405 nm. The Anycubic Photon Mono M3 printing machines has a build volume of 180 x 163 x 102 mm. The printers employ a 405 nm Para LED matrix as a UV light source, along with an LCD screen to exhibit a masked image of each sliced data. This study specifically examined the mechanical properties of the standard UV resin used in the Anycubic printer, despite the fact that it can also accommodate other resins like as UV tough resin, dental resin, UV resin for casting, and acrylonitrile butadiene styrene (ABS). The Standard UV Resin is a UV-curable resin with high precision. It cures when exposed to a UV curing wavelength ranging from 365 to 410 nm, often within 5 to 15 seconds (Temiz, 2023). The composition comprises acrylate oligomer, acrylate monomer, and a photoinitiator. The material utilised was a conventional UV resin, with specific characteristics outlined in Table 1.

Table 1. Characteristics of conventional UV resin.

Properties	Value
Viscosity, cP or mPa·s	150-200
Density, g/cm^3	1.05-1.25
Molding shrinkage, %	3.72-4.24
Tensile strength, MPa	36-52
Flexural strength, MPa	50-70
Surface hardness, HD	84
Flexural modulus, MPa	1200-1600

The Anycubic wash and cure plus post printing washing and curing machine was used to do the final curing and washing operation. The dimensions of this equipment for washing are 192*120*290 mm, while the dimensions for curing are 190*245 mm.

2.2 Sample Production

The development of a dog bone tensile test specimen involved following the ASTM D638 standard test technique for evaluating the tensile characteristics of polymers. Specimen dimensions were derived from an ASTM D638 Type 4 model, and Solidworks was used to build the specimen's computer-aided design (CAD) (Anonymous, 2022). The created samples were saved in STL format and subsequently sliced using Anycubic Photon Workshop 3D Slicer Software. The layer thickness in the slicing parameters remained consistent at 50µm for all samples. All settings, except for the exposure time, are predetermined by default. The samples were generated using 4 distinct parameters, which varied based on the time of exposure. Initially, all layers were generated using a 3-second exposure time, followed by the generation of all layers using a 15-second exposure time.

Subsequently, the sample was divided into three sections, with the bottom and top layers being generated using a 3-second exposure time, while the layers in the middle were generated using a 15-second exposure time. At last, both the top and bottom levels were created with a 15-second exposure period, while the middle layers were formed with a 3-second exposure time. The three distinct zones were obtained by adjusting the exposure period on the MSLA screen during printing, leading to differing levels of exposure. In order to finalize the polymerization process, it is advisable to cleanse 3D printed items using a solvent to eliminate any unpolymerized resin, and subsequently transfer them to a gentle polymerization chamber (Wada et al., 2022). In order to fully evaluate the impact of post curing, the samples were individually analyzed both prior to and after to the post curing process. Following the printing procedure, the printed parts were extracted from the build platform and cleaned of excess resin through rinsing with isopropyl alcohol (IPA). Each sample used for the tensile and hardness tests was washed in an Anycubic wash & cure 2.0 machine with IPA for two minutes. After washing the samples with IPA, the MSLA 3D printer samples were divided into two groups. Half of the cleaned samples were then placed in the curing chamber of the Anycubic wash & cure 2.0 machine and underwent a 5-second final curing process to investigate the impact of this final step. This post curing protocol is similar to those used in dental and medical applications, however, it allows for constant light intensity and adjustable time. This technology is also widely used in the dental industry for manufacturing components using resins like dental temp and surgical guide, which are subsequently subjected to post-curing. Figure 1 displays the schematic depiction of the generated samples.

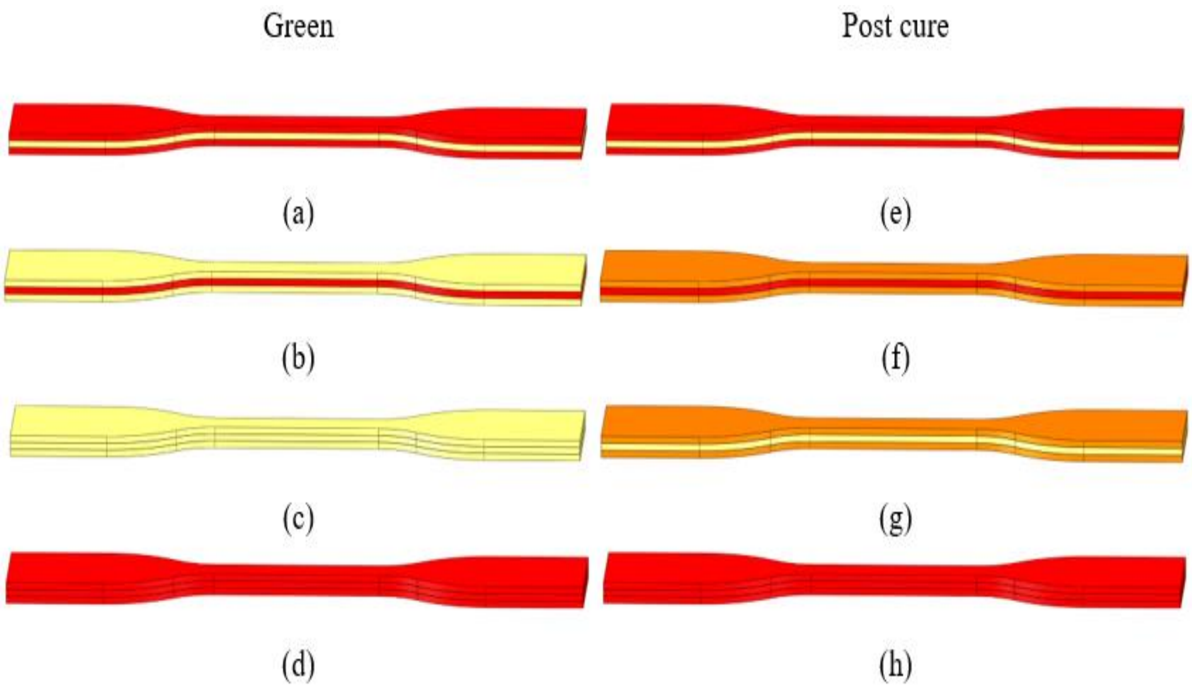

Figure 1. Layers in (a) and (e) were exposed for 15 s, while layers in the middle were exposed for 3 s, layers in (b) and (f) were exposed for 3 s, while layers in the middle were exposed for 15 s, layers in (c) and (g) were exposed for 3 s, and layers in (d) and (h) were exposed for 15 s

2.3 Mechanical Testing

The application of several criteria resulted in the production of a total of eight samples. A tensile test was conducted using the AG-50 kN Shimadzu Autograph under controlled settings, maintaining a constant crosshead speed of 5 mm/min and operating at room temperature. Tensile testing was performed using the parameters specified in ASTM D638 (Anonymous, 2022). The specimens were subjected to tensile testing until they reached the point of fracture. To reduce the influence of fluctuations and unpredictable errors, each recorded value in the dataset corresponds to a minimum of three valid tests. No instances of further peaks in strength were seen in the samples. The UTS was identified as the maximum stress measurement ever recorded. In addition, for the purpose of measuring hardness (Shore D), two distinct samples were created, each with dimensions of 20 mm x 20 mm x 10 mm, with an exposure time of 3 seconds and 15 seconds, respectively. Hardness values of these samples were measured separately before and after post curing.

3. RESULTS AND DISCUSSION

Each sample was manufactured successfully in accordance with the given parameters. Although not a significant constraint identified during the investigation, minor concerns emerged regarding the adherency of the printed samples to the build tray, particularly when distinct exposure periods were employed for each layer. In particular, when using a shorter exposure time (3 seconds) for the outer layers and a longer exposure time (15 seconds) for the middle layers, cases were observed where the sample did not always stick to the tray during printing. However, it is important to mention that samples could also be effectively generated with a first layer exposure period of 3 seconds. The stress-strain curves for each of the chosen exposure times are depicted in Figure 2. The tensile test results demonstrate that increasing exposure time leads to an increase in the elastic modulus. According to the literature (Bazyar et al., 2023), it is typical for the elastic modulus to rise as the time of exposure increases. Equation (1) confirms that the primary cause for this phenomenon.

$$\phi (z,t) = 1 - \exp(-KI_0 \exp(- \mu z)t) \quad (1)$$

The variables in the equation are defined as follows: ϕ represents the ratio of monomer-to-polymer conversion, t represents the exposure duration, K represents the effective reaction conversion rate of the material, μ represents the attenuation coefficient, and z represents the direction of the manufacturing process (Bonada et al., 2017). As the exposure time increases, more monomers undergo polymerization, as indicated by Equation (1). Therefore, the increase in exposure time leads to a rise in Young's modulus and other mechanical properties (Ambrosio et al., 2020; Temiz, 2023). This is confirmed by the tensile results in Figure 1 (a) in the absence of final curing. However, a negative correlation was observed between exposure time and elongation. The post-curing process enhanced the tensile strength and Young's modulus values, as illustrated in Figure 2. Prior research findings indicate that the tensile strength of various resins exhibited a rise ranging from 29% to 215%, while Young's modulus showed an increase ranging from 33% to 172% (Riccio et al., 2021). These results validate the alteration observed in the stress-strain curve depicted in Figure 2 after the post-curing process.

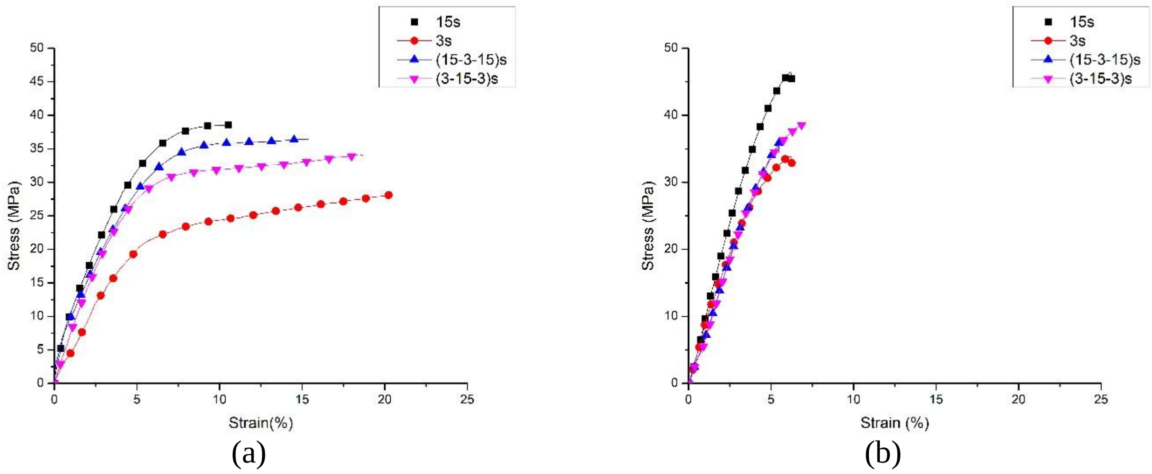

Figure 2. Curves of stress and strain for exposure durations of 3s, 15s, 15-3-15s, and 3-15-3s are presented a) green and b) following post cure

The data for ultimate tensile strength and elongation are displayed in Figure 3. The elongation and ultimate tensile strength values of all specimens have been determined using the tensile test. Figure 3 (a) indicates that the ultimate tensile strength of green specimens, which were produced for 3 seconds exposure time, was measured to be 28.08 ± 0.4 MPa. By extending the time spent of the exposure to 15 seconds, there was a significant increase in the ultimate tensile strength, which reached a value of 38.59 + 0.4 MPa. The post cure specimens, produced with an exposure time of 3 seconds, exhibited an ultimate tensile strength of 33.87 ± 1.04 MPa. By increasing the duration of exposure to 15 seconds, there was also a notable rise in the ultimate tensile strength, which reached a value of 46.46 ± 0.9 MPa. Two distinct materials were generated as FGMs. Designated as (15-3-15), these objects have the central area exposed for a duration of 3 seconds, while the edges are exposed for 15 seconds. Similarly, designated as (3-15-3), these objects have the central area exposed for 15 seconds, while the edges are exposed for 3 seconds. The green specimens produced during 15-3-15 s exposure time had an ultimate tensile strength of 35.85 ± 0.4 MPa. After post curing, the ultimate tensile strength was measured as 36.45 ± 1.1 MPa. The green specimens, which were exposed for 3-15-3 seconds, exhibited an ultimate tensile strength of 34.15 ± 0.8 MPa. After the post curing process, the ultimate tensile strength was determined to be 38.77 ± 0.7 MPa.

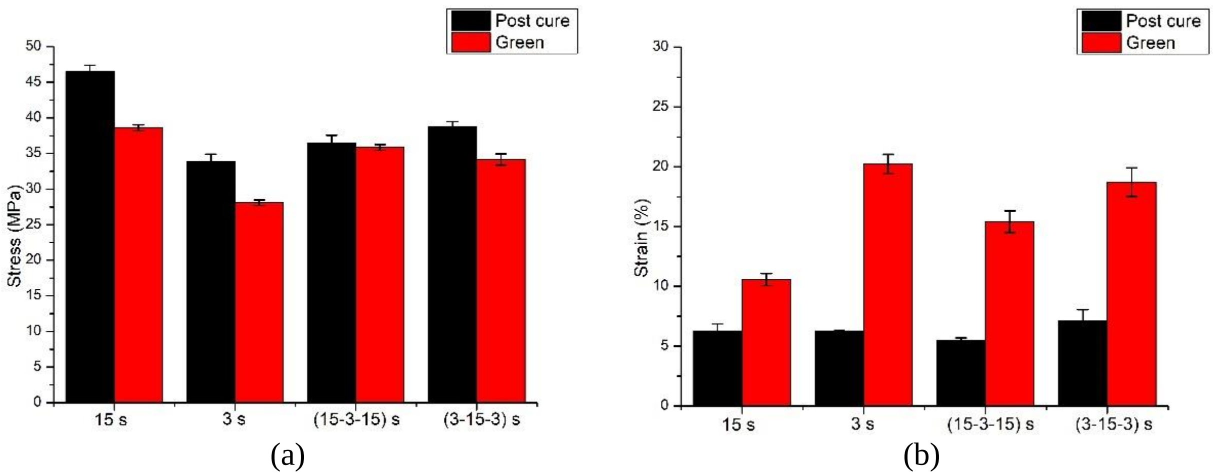

Figure 3. Depending on the exposure time, (a) ultimate tensile strength and (b) elongation

Furthermore, Figure 3 (b) displays the maximum strain values. The graph clearly illustrates a decrease in strain levels following the final curing process. The reduction in amount is more pronounced for a low curing value (3 seconds exposure time), but comparatively less significant at a high curing value (15 seconds exposure time). Understanding the hardness values of each material in FGM design is a crucial component for optimizing material performance, durability, and life. This can be utilized to attain more precise and efficient material designs in a multitude of industrial and technical applications. Hardness is a significant mechanical property of resins, since it determines their ability to withstand wear and deformation (Vasques et al., 2019). Figure 4 displays the Shore D hardness values of samples obtained at various exposure durations, both before and after post curing.

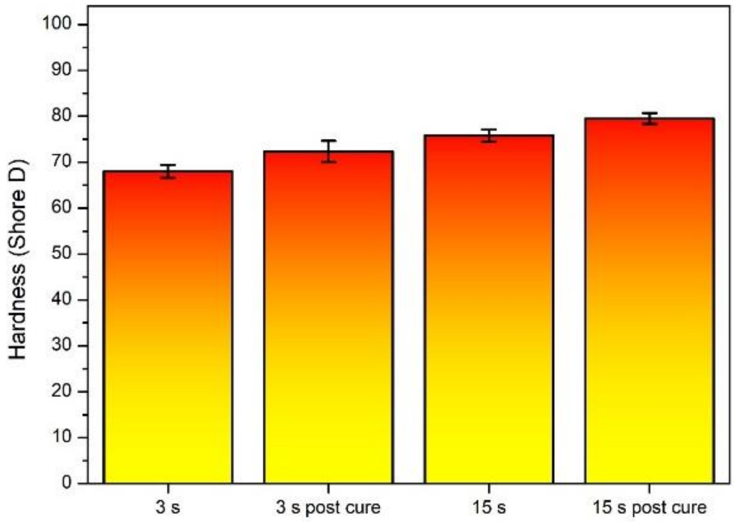

Figure 4. Hardness value of the specimens

Increasing the time of exposure enables a more comprehensive polymerization process of the resin, resulting in a greater degree of conversion of monomers into polymer chains. In addition, post-curing enhances the progress of the curing reaction, eliminating any remaining uncured monomers and enhancing the overall uniformity of the material. The improved curing efficiency leads to the observed enhancement in mechanical characteristics, as the material becomes more homogeneous and structurally resilient. Figure 4 illustrates a direct correlation between the exposure time and the hardness value of the material, indicating that as the exposure time rose, the hardness value also increased. Furthermore, post curing results in a heightened level of material hardness. The hardness of the sample, which was initially 68, increased to 72.33 after post curing, following a 3-second exposure duration. The hardness of the sample, obtained with a 15-second exposure time, was 75.8 prior to post-curing and increased to 79.5 after post-curing. The increase in hardness of the material with longer exposure time and post-curing aligns with findings in the literature. A study on 3D-printed orthodontic aligner material reported that longer curing times resulted in increased surface hardness of the printed objects (Wada et al., 2022). Additionally, post-curing has been shown to enhance the mechanical properties of 3D-printed materials. For instance, a study on the influence of post-processing methods on the Knoop hardness of photosensitive resins used in dentistry found that post-curing significantly increased the hardness of the materials (Vasques et al., 2019). These findings support the observed increase in hardness with post-curing in the samples. It is important to note that the choice of 3D printing technology can impact the mechanical properties of the printed objects. For instance, a study comparing different 3D printing technologies found that SLA printers provided higher surface hardness compared to DLP printers (Wada et al., 2022). The layers and graded transitions were also studied by examining microscopic photographs of the samples. Microscopic images of the materials are depicted in Figure 5.

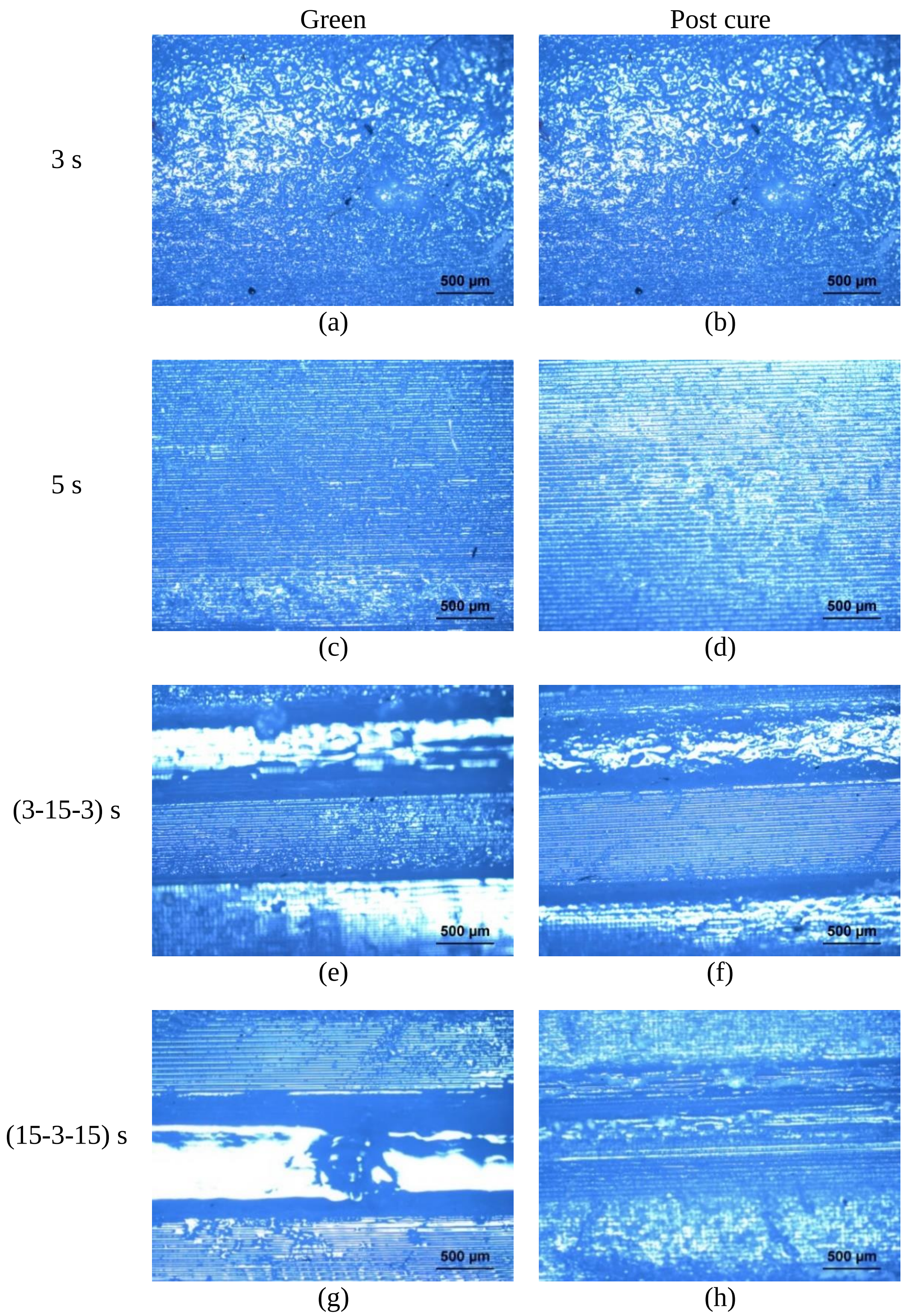

Figure 5. Microscopic images of the different exposre time sambles (a) 3 s, (b) 3s with post cure, (c) 15 s, (d) 15 s with post cure, (e) (3-15-3) s, (f) (3-15-3) s with post cure, (g) (15-3-15) s, and (h) (15-3-15) s with post cure

Upon analyzing Figure 5, it is evident that the layer transitions in the samples created with a 15-second exposure time are more distinct, whereas the layer transitions are not observable in the samples produced with a 3-second exposure period. Furthermore, the transitions in grades of FGAM specimens are more distinctly visible, particularly in specimens with a green coloration.

In conclusion, the elastic section is typically more susceptible to deformation. Thus, in the process of conducting tensile testing, a significant portion of the deformation is likely to take place in the more elastic section. Given its inherent rigidity and resistance, the hard section frequently serves as the site where cracking or fracture initiates. Cracks frequently initiate and spread in the boundary zones of materials due to the contrasting mechanical characteristics of hard and soft materials. Instead of sudden variations in mechanical characteristics across different areas of the printed part, a smooth transition can be incorporated. This can be accomplished by incrementally modifying the exposure time throughout each layer, facilitating a more seamless transition between materials that have distinct properties. This method has the potential to reduce stress concentration at the borders, which in turn can assist prevent the beginning and spread of cracks.

4. CONCLUSION

This study introduced an easy and useful technique for printing polymer materials with distinct characteristics in each layer using MSLA printers. The tensile test samples were printed with different characteristics in their inner and exterior regions, and their mechanical properties were examined. In addition, an investigation was conducted to evaluate the alterations in the mechanical characteristics of these graded printed samples subsequent to the post curing process. It has been noted that materials manufactured with longer exposure times exhibit higher hardness, and the post curing process further enhances the material's hardness. Increasing exposure time polymerizes the resin more thoroughly, converting monomers into polymer chains. Post-curing also accelerates the curing procedure, eliminates uncured monomers, and improves material consistency. Improved curing efficiency makes the material more uniform and structurally resilient, improving mechanical properties. The samples, when manufactured with a more rigid interior and a more flexible outside, exhibited a decreased ultimate tensile strength compared to those made with a flexible interior and a rigid exterior. However, this trend was reversed after undergoing post curing. This approach has the capability to selectively generate specific regions of the material with increased elasticity or rigidity, depending on the desired qualities. Structural engineering applications in industries like aerospace or automotive often necessitate components that possess a blend of rigidity and flexibility. Structures that require both internal support and outward stress absorption, such as composite panels for aircraft or automobile body panels, could benefit from components that have a rigid inner and a flexible exterior. When it comes to protective gear and sportswear, such as helmets, padding, or athletic footwear, it is crucial to have materials that provide both impact resistance and flexibility. Utilizing samples that have an inflexible core and adaptable exterior could offer improved defense against impacts while simultaneously preserving the wearer's comfort and mobility. Biomedical engineering frequently necessitates the use of materials that imitate the mechanical characteristics of natural tissues for implants, prostheses, and medical devices. Implants or surgical instruments that have a hard core and a flexible outer layer offer advantages by providing stability during insertion and minimizing tissue stress.

5. ACKNOWLEDGEMENTS

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6. CONFLICT OF INTEREST

The author confirms that, to the best of their knowledge, there are no common interests or conflicts of interest with any organization, institution, or individual that could potentially impact the review process of the paper.

7. AUTHOR CONTRIBUTION

Abdurrahim TEMİZ contributed determining the concept of the research and research management, design process of the research and research management, data analysis and interpretation of the results, critical analysis of the intellectual content, preparation of the manuscript, and final approval and full responsibility.

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