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Investigation of the effect of dip coating with silica reinforced epoxy composite on the mechanical properties of 3D printed PLA materials

3B baskılı PLA malzemelerin silika takviyeli epoksi kompozit ile daldırmalı kaplanmasının mekanik özelliklere etkisinin incelenmesi

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Abstract

Coating parts with a composite improves mechanical strength, especially for low-strength materials. Ceramic reinforced polymer composites are one such coating, used in many industries to produce durable materials. In the study, composite materials were produced by coating the outer part of PLA parts produced with 10%, 15% and 20% fill densities with a 3D printer using additive manufacturing and material coating methods, with ceramic reinforced epoxy materials containing 15% silicon dioxide by weight. The impacts of the manufacturing parameters on tensile strength and hardness were investigated and SEM analyses were performed. The study concluded that the coated sample with an filler density of 20% demonstrated a maximum tensile strength of 22.34 MPa and a maximum hardness value of 74.7 Shore D. The SEM results showed the coatings were evenly deposited on the part's surface. The findings indicate that the coating of 3D-manufactured materials possesses considerable potential to produce high-performance materials.

Keywords: Composite materials, Dip coating, Mechanical properties, Silica

Öz

Bir malzemenin yüzeyine, mekanik özelliklerini iyileştirmek amacıyla kompozit bir kaplama uygulanması işlemi özellikle düşük mekanik dayanımlı parçalar için önemlidir. Kaplama için kullanılan kompozitlerden birisi de seramik katkılı polimer kompozitlerdir. Birçok endüstride yaygın olarak kullanılan bu kompozitlerin, endüstriyel kaplama yönteminde kullanımıyla daha dayanımlı malzeme üretimi sağlanabilmektedir. Bu çalışmada, eklemeli imalat ve malzeme kaplama yöntemleri kullanarak 3B yazıcı ile %10, %15 ve %20 iç dolgu oranlarında üretilen PLA parçaların dış kısmı ağırlıkça %15 silisyum dioksit olan seramik takviyeli epoksi malzemeler ile kaplanarak kompozit malzemeler üretilmiştir. Üretim parametrelerinin çekme dayanımına ve sertliğine etkisi araştırılarak SEM analizleri gerçekleştirilmiştir. Çalışma sonucunda iç dolgu oranı %20 olan kaplamalı numunenin 22,34 MPa ile maksimum çekme dayanımına ve 74,7 Shore D ile maksimum sertlik değerine sahip olduğu bulunmuştur. SEM sonuçları ile kaplamaların parça yüzeyine homojen bir şekilde sağlandığı desteklenmiştir. Elde edilen sonuçlar, 3B üretilen malzemelerin kaplanması ile yüksek performanslı malzemeler üretme konusunda önemli bir potansiyele sahip olduğunu kanıtlamaktadır.

Anahtar kelimeler: Kompozit malzemeler, Daldırmalı kaplama, Mekanik özellikler, Silika

1 Introduction

Additive manufacturing (AM) has caused a paradigm change in the manufacturing sector across a range of industries. This technological advancement has facilitated the fabrication of complex geometries with unparalleled customisation and a concomitant reduction in waste. AM has evolved from a rapid prototyping tool to a comprehensive manufacturing solution using a variety of materials [1].

AM technology offers superior design flexibility and reduces waste compared with conventional subtractive methods [2].

AM processes are characterised by the production of physical objects from digital information, with the fabrication occurring in a sequential manner, whether in a linear or layer-by-layer configuration. The scope of AM processes encompasses the direct fabrication of models, end-use components, prototypes, and assemblies, in conjunction with the production of fixtures, moulds and tooling for indirect fabrication [3].

It is apparent that the most prevalent 3D printing technology at present is unquestionably fusion deposition modelling (FDM), a technique pioneered by Stratasys in the late 1980s and regarded as one of the most extensively utilised AM technologies [1].

FDM is a widespread extrusion technique whereby a material is fed through a heated nozzle, melted, and deposited in layers. The nozzle is generally capable of movement in the horizontal direction, and the platform moves in the vertical direction following the deposition of each novel layer. Nevertheless, it should be noted that in

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certain FDM technologies, the nozzle is capable of movement in both the horizontal and vertical axes [4].

The primary material utilised by FDM is thermoplastics, which possess a number of advantageous properties. These include the capacity to be readily heated and reshaped, thus rendering them suitable for a broad spectrum of applications. In the realm of FDM, polylactic acid (PLA) stands out as a noteworthy material due to its status as a biodegradable thermoplastic, a characteristic that renders it an environmentally friendly option [1].

Furthermore, the utilisation of PLA filament is predominant due to its cost-effectiveness, comparatively low melting point, and linear polymer chains [5].

It has been demonstrated that the parameters of the printing have a marked effect on the characteristics of the components. This has the result that the quality and processing time are enhanced. The parameters of the FDM process can be classified into several variables, including those relating to slicing parameters, build direction, layer thickness, air gap, flow rate, deposition rate and raster angle [6].

In their natural state, polymeric materials demonstrate certain deficiencies, including inadequate strengths and rigidity, and low operating temperatures, factors that collectively impose considerable constraints on their utilisation. Consequently, numerous researchers have incorporated filler additions, which have been demonstrated to enhance the mechanical characteristics of the polymer and yield superior outcomes. The primary objective of polymer filler was to decrease the cost of the material by incorporating a lower-cost filler. Silica dioxide, abbreviated as SiO_2, is a filler addition that has been employed in a multitude of experiments. Silica, in general, has the capacity to blend with a variety of polymeric materials, thereby enhancing the final properties and qualities of the resulting composite. Furthermore, the utilisation of silica as a filler has been a subject of extensive study, with a view to enhancing the mechanical behaviour of polymeric materials. As demonstrated in extant literature, the incorporation of silica as a reinforcement agent has been demonstrated to enhance the characteristics of polymer composites, including tensile strength and elastic modulus [7].

A composite material can be defined as an intelligent combination of two or more component parts that are mixed and insoluble in each other at the macroscopic level. The reinforcement can take various forms, including particles, fibres, flakes or particles. A key research area in composite materials is the development of strong, lightweight structural composites. The utilisation of these materials is pivotal in complex structures, including those employed in the automotive sector, the aerospace industry, and the fabrication of substantial wind turbine blade structures [8].

Polymers are popular in engineering because they are cost-effective and environmentally friendly [9].

Polymer matrix composite (PMC) is a composite of a polymer matrix and a filler material. The properties of PMCs are known to be contingent on the characteristics of the filler material and matrix, the interface and dispersion of said filler material in the polymer matrix, as well as the configuration and orientation of said filler material within said polymer matrix [10].

From a production perspective, the fabrication of PMC materials is more expeditious than that of carbon matrix, ceramic matrix, or metal matrix composites. Thermoplastic polymers are extensively utilised due to their advanced mechanical properties, exceptional resistance to chemical reactions, and reduced cost compared to metal matrix composites [11].

Epoxy is a polymer that is utilised extensively because of its simplicity of processing, high adhesion and high chemical resistance. Epoxy-based composites are frequently employed in aerospace, automotive and marine applications. Epoxy has been extensively utilised in the domain of composite applications as a polymer matrix. Epoxy resin is widely regarded as the most significant polymer. Epoxy is often used in composites due to its high strength, stability and electrical properties [12].

Epoxy-based polymer composites have been identified as a significant category of material due to their utilisation in multiple sectors as a substitute for conventional materials. Various fillers are used to enhance and modify the strength of composite materials. In numerous instances, the significance of a material's mechanical properties is regarded as paramount, superseding other attributes [13].

The addition of particulate fillers to composites is known to have a beneficial effect on their mechanical strength. The incorporation of fillers has been demonstrated to enhance a range of properties, including mechanical strength, thermal conductivity and thermal stability. Consequently, there is a preference for the utilisation of polymer composites over pure polymers in a variety of applications. A plethora of inexpensive inorganic particulate materials, including mica, calcium carbonate, kaolin clay, carbon nanotubes, titania and silica, are frequently employed as fillers to augment the thermal and mechanical characteristics of polymers. Silica is of particular interest as a filler due to its stability and non-reactivity. This has led to its extensive use in numerous applications to provide improved properties in composites [14].

A plethora of studies have been conducted on SiO_2 reinforced epoxy matrix composite materials, as evidenced by the extensive body of literature on the subject.

Jang et al. investigated the in-situ effective material characteristics of micron-sized silicon dioxide particles in SiO_2 particle-reinforced polymer composite materials. Following the integration of the particulate matter, the cure agent was introduced and dispersed. The effect of loading fraction of silicon dioxide particles was investigated by making seven composite specimens at varying particle loadings (volume fractions ranging from 5% to 35%). The effective modulus of elasticity and coefficient of thermal expansion of micron-sized SiO_2 particulate matter demonstrate that the in-situ particulate characteristics are significantly divergent from the respective characteristics of bulk or film-form materials [15].

Poh et al. explored the tensile and thermal characteristics of epoxy composites that had been impregnated with mica, calcium carbonate, and silica. These minerals were utilised

as fillers in the manufacture of epoxy thin film composites intended for use in capacitors. The outcomes of the study evidenced that the tensile properties of epoxy thin films with 20% filler loading by volume exhibited a decrease as the filler loading increased, a phenomenon attributed to the onset of brittleness [16].

Jo and Lee examined the mechanical characteristics of epoxy composites reinforced with micrometre-sized silica particles using experimental and empirical modelling. For all samples utilised in the study (ranging from the base to the sample content 70 wt% silica filler), the tensile strength and elastic modulus exhibited a gradual increase of 8-10% and 51-55%, accordingly, in comparison to the base specimens. However, the ductility of the specimen diminished by 34% [17].

AbdulRazaq et al. explored the characterisation of the mechanical behaviours of epoxy-silica functionally graded materials. The fabrication of the functionally graded material was undertaken utilising the method of hand lay-up. The material consists of silicon dioxide reinforced epoxy resin with a particle size of 100 µm with weight percentages ranging from 0% to 80%. The experimental findings demonstrated that augmenting the proportion of silicon dioxide enhances the mechanical characteristics, with the increase in the elastic modulus being in direct proportion to the weight percentage of the reinforcing material. The modulus exhibited an almost linear increase as the level of added silica particles increased [18].

Bharadwaja et al. investigated the tensile and flexural behaviour of epoxy and SiO_2 composites. The flexural strength of the composite (Epoxy + SiO_2) exhibited an increasing trend with an increase in SiO_2 content up to 4% by volume, followed by a decrease of 5% [19].

Abd et al. carried out a comparative exploration into the mechanical characteristics of silica epoxy composites, examining the impact of micro (100 µm) and nano (12 nm) silica particles on the mechanical characteristics of the epoxy resin. The preparation of micro and nano composites was undertaken through a three-step process, incorporating varying volume fractions of micro and nano particles (from 1 to 20 vol%). The study's outcomes indicated that the composites presented enhanced mechanical properties relative to those of pure epoxy resin [20].

3D printed products have many applications and are subject to various environmental factors. In conditions of high humidity and ultraviolet radiation, there is a greater need for protective coatings that also enhance the appeal of 3D-printed objects. The establishment of an effective surface system, encompassing polymer surfaces and coatings, necessitates a comprehensive comprehension of surface properties, with a particular emphasis on surface wettability. These properties are inherently associated with the adhesion of coatings to substrates. The surface properties of polymers are such that surface treatment is only possible with suitable coatings. Furthermore, the application of coatings to 3D printed models is possible through myriad technologies, contingent on the coating composition and characteristics, the object's geometry, and its dimensions [21].

A substantial number of studies have been performed in the extant literature investigating the surface and mechanical properties of components through the process of coating with epoxy, as well as investigating the surface properties of components through the process of coating with silica-filled epoxy matrix composite material.

Teh et al. investigated the characteristics of epoxy resin-coated silica-filled composite materials. The successful preparation of novel epoxy resin-coated silica filler composites was achieved through the utilisation of a mechanical mixing method. The efficacy of this technique was demonstrated by its superiority to conventional mixing techniques in the production of composites with high filler loading [22].

Lee et al. fabricated a superhydrophobic surface using a filament (PLA) 3D printer and immersion coating with silica nanoparticles. An investigation into the wettability of the 3D-printed component was conducted using a method that involved the measurement of both static contact angles and sliding angles. These measurements were taken prior to and following the dip-coating procedure. The process was found to be readily implementable with commercially available FDM 3D printers and has potential applications in fluid position control and reduced water adhesion [23].

Yang et al. focused on the fabrication of hydrophobic surfaces on PLA by FDM. In the study, the focus was on the employment of FDM 3D printing technique in the preparation of hydrophobic coatings on PLA parts, with a particular emphasis on its design and processing flexibility. Moreover, the investigation explored how the parameters employed in printing processes influenced the subsequent surface roughness and wettability of the test pieces [24].

Tu et al. carried out the deposition of SiO_2/epoxy composite coatings on the epoxy resin surface using a spraying technique. The objective of the study was to elucidate the influence of surface coating on the properties of surface charge deposition in epoxy resin. The investigation into the charge deposition on the surface was conducted utilising the electrostatic probe technique. The study found that micron SiO_2 particles (1-3 wt%) or nano SiO_2 particles (3 wt%) can effectively suppress the surface charge of epoxy resin [25].

Hiremath et al. investigated the effect of epoxy coated 3D printed polymers on the mechanical behaviour of materials. The investigation involved the utilisation of polymers like PLA filaments in the fabrication of 3D-printed components with different thicknesses of layers. The mechanical behaviour of the samples that underwent printing and epoxy resin coating were subjected to rigorous analysis [26].

The objective of the present study is to investigate the manufacturing of composite materials through the coating of silicon dioxide-reinforced epoxy material on the exterior surfaces of PLA components manufactured via the FDM method. The current study investigates the influence of production parameters on the mechanical characteristics of these composite materials. The utilisation of AM and material coating methods in the production of composites is a key advantage of the present study. The mechanical strength of the composites manufactured was assessed by

conducting tensile and hardness tests. It is thought that the production of parts with increased mechanical strength by coating the outer part of PLA materials, which can be produced quickly at low filling rates, with silica reinforced epoxy composite material will be industrially beneficial, especially the production of parts such as mounting brackets, which are important in the automotive sector, can be provided by this method. It is hypothesised that the analysis of the impact of the production parameters employed in this study on the mechanical properties will significantly contribute to the existing body of literature.

2 Material and method

In this study, 3D parts with 10%-15% and 20% internal filling ratios in gyroid filling pattern were produced by utilising the Creality CR-M4 3D Printer. The production process was executed through the implementation of the FDM printing method, employing PLA material. The material has achieved a notable level of popularity within the domain of 3D printing, primarily due to its environmental sustainability and cost-effectiveness. In this investigation, the Porima brand was utilised in grey, with a diameter of 1.75 mm. The FDM printing parameters comprised a thickness of layer of 0.2 mm, a printing temperature of 220 °C and a printing table temperature of 65 °C. The printing speed was set at 60 mm/s, and a wall thickness of 1.2 mm was employed. The properties of the PLA are outlined in Table 1.

Table 1. PLA mechanical properties [27]

Mechanical properties	Values
Tensile Strength	15.5 MPa-72.2 MPa
Young's Modulus	2.020 GPa-3.550 GPa
Elongation at Break	0.5%-9.2%
Flexural Strength	52 MPa-115.1 MPa

In the domain of AM of three-dimensional objects, the initial step entails the conception of the desired three-dimensional shape utilising CAD (computer-aided design) software. Subsequently, the geometry undergoes conversion to the stl (standard tessellation language) format and is then sliced into layers by the Cura slicing software. The three distinct fill densities employed as printing parameters in this study are defined within the 3D printer software. During the printing process, each layer is printed successively, resulting in the production of the 3D component in accordance with ASTM standards.

In the current study, epoxy resin was utilised as the matrix, with SiO_2 particles serving as the filler material. Silicon dioxide is a cost-effective material that is readily available in nature and can be easily transported. The silicon dioxide was obtained from a local company, and its mean particle size was determined to be 44 µm. Epoxy resins are utilised extensively in a broad range of industrial sectors, owing to their remarkable mechanical and chemical properties. The weight ratio of the epoxy and hardener mixture utilised in this study is 2:1 (epoxy: hardener), both of which were procured from a local supplier.

In this study, 15 wt% silicon dioxide was added to the epoxy matrix with the objective of producing silicon dioxide-reinforced epoxy polymer materials for coating. In order to obtain the required homogeneity in the structure of SiO_2 reinforced epoxy polymers, the matrix and filler materials were subjected to a mechanical agitation process in a mixer operating at a speed of 3000 rpm for a duration of 45 minutes.

Jiang et al. revealed that an increase in dispersion time resulted in a more homogeneous dispersion; however, an excessively prolonged dispersion could not further enhance the dispersion effect [28].

To reduce production time and enhance the mechanical behaviours of the FDM parts, SiO_2 reinforced epoxy polymer material was used to coat the 3D part using the dip coating process. The process involved dipping and removing using a router table to ensure a homogeneous and consistent coating of the SiO_2 reinforced epoxy polymer blend on the exterior of the 3D printed part, and the immersion time was set to 5 s. The coating thickness of the samples was measured to be 250 µm (±25 µm) with a micrometer. Thickness measurements were taken from different parts of the samples and repeatedly. Figure 1 shows the methodology used to inject the SiO_2 reinforced epoxy polymer into 3D components produced by the FDM technique. Following the coating process, the specimens were subjected to 72 hrs curing period at ambient temperature.

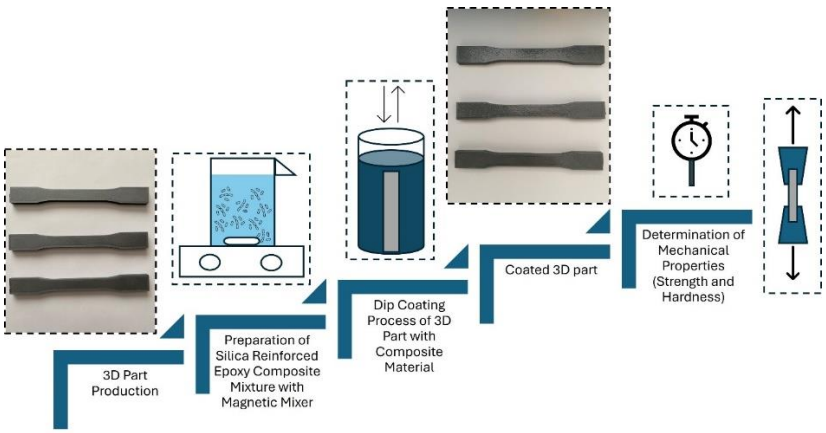

Figure 1. Production methodology

The coating material fills the surface voids by penetrating into the micropores and rough areas of the PLA surface and then hardens to form a mechanical interlocking effect. The silica particles increase the spreadability and adhesion strength of the coating to the surface, ensuring a strong bonding of the coating to the PLA surface.

The tensile testing specimens were manufactured in accordance with the provisions stipulated in ASTM D638-I, with dimensions of 165 mm in length, 19 mm in width, and 7 mm in thickness. The experimental procedure involved conducting the tensile tests at ambient temperature using a Shimadzu universal testing machine. The samples were exposed to a constant feed rate of 3 mm/min, and the resulting maximum tensile strengths were determined. Three samples were produced for each type of tensile test specimen, and the results were averaged. Figure 2 illustrates the appearance of the coated 3D parts during the tensile test.

Figure 2. Coated 3D part during tensile test

In accordance with the prevailing ASTM D2240 standard, a hardness (Shore D) test was also conducted on the specimens. The image of the coated 3D parts during the hardness test is shown in Figure 3. Each hardness value was subjected to five repetitions and then averaged.

Figure 3. Coated 3D part during Shore D hardness test

The nomenclature employed for the specimens produced in this study incorporates a systematic classification system based on the silica content and filler density. In this classification system, the ratio following the letter I denotes the filler density, with the subsequent letter indicating whether the specimen is non-coated (N) or coated (C). The graphs are accompanied by error bars, which are indicated by a line.

As illustrated in Figure 4, the coating surfaces of the 3D parts were analysed utilising a Scanning Electron Microscope (SEM). The analysis demonstrated that the silica particles were distributed uniformly throughout the epoxy.

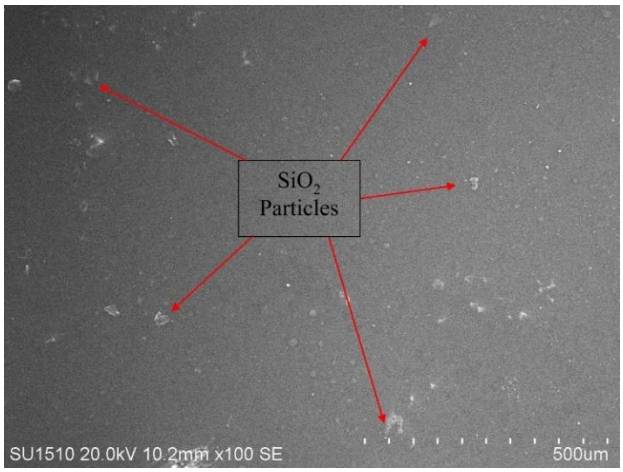

Figure 4. SEM image of sample I10C

3 Results and discussion

The force-displacement graphs, maximum tensile strengths and elastic modulus of 3D-printed PLA specimens manufactured with varying uncoated filler densities and 3D-printed PLA specimens coated with micro silica-reinforced epoxy are demonstrated in Figure 5, Figure 6 and Figure 7, respectively.

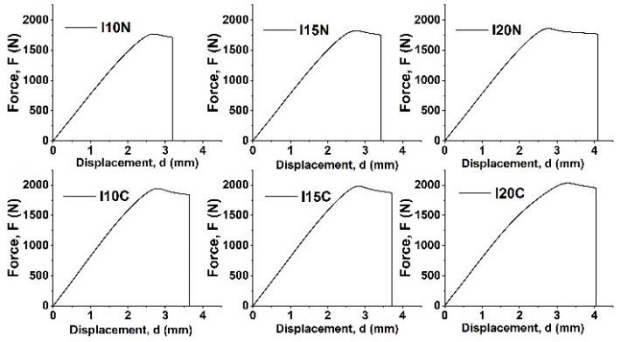

Figure 5. The force-displacement graphs

The study revealed that the maximum tensile force was attained by the coated specimen with a filling ratio of 20%, while the minimum tensile force was obtained by the uncoated specimen with a filling ratio of 10%.

The study's findings indicate that the filler density exerts a notable influence on the tensile strength values of 3D-

printed PLA samples. The enhancement in filler density resulted in a considerable increase in the tensile strength values of the 3D-printed PLA components.

Filler density has been shown to be directly proportional to strength. It has been observed that specimens with higher filler density exhibit enhanced interlayer bonding and increased resistance to deformation, attributable to reduced air voids. Increasing the filler density has been found to increase the mechanical strength of the part due to the interlayer bonding between successive layers. A lower filler density has been demonstrated to increase the production speed and reduce the amount of material required [29].

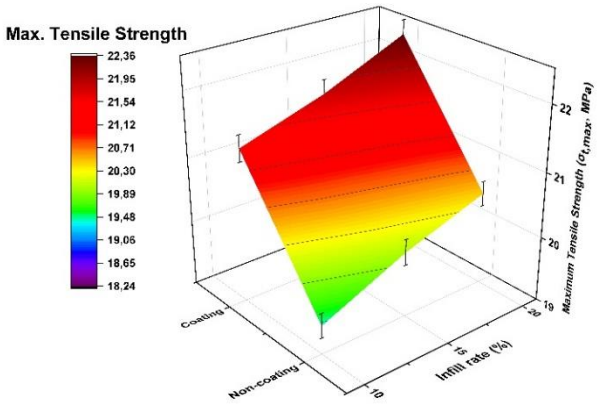

Figure 6. Maximum tensile strength

Maguluri et al. examined the impact of FDM processing parameters on the mechanical behaviours of PLA components, utilising the Taguchi method. The investigation encompassed the analysis of the effect that filler density, printing speed, and nozzle temperature have on the tensile strength of specimens fabricated using PLA filament. The findings revealed that an augmentation in filler density, ranging from 50% to 100%, resulted in a substantial enhancement in elastic modulus, tensile strength, and breaking stress, respectively [30].

In the uncoated specimens with varying filler densities, the specimen with a 20% filler density was found to demonstrate the highest tensile strength, with a recorded value of 20.43 MPa. Similarly, among the specimens coated with different filler densities, the specimen with a 20% filler density demonstrated the highest tensile strength, with a recorded value of 22.34 MPa.

The results also demonstrate the variation in tensile strength of uncoated and coated PLA samples at the same filler density. A comparison of the uncoated and coated samples at a 10% filler density reveals that the tensile strength increased by 9.93% when the sample was coated. A similar trend was observed when uncoated specimens with 15% and 20% filler density were compared with coated specimens with the same filler density, exhibiting an increase in tensile strength of 8.84% and 9.34%, respectively. The coated specimen with 20% filler density demonstrated the highest tensile strength of 22.34 MPa among all specimens.

As demonstrated in the existing literature, the modulus of elasticity and tensile strength values of PLA samples are susceptible to variation in accordance with the parameters employed during the printing process.

Seol et al. explored the parameters of filler density printing with respect to the mechanical behaviours of 3D-printed PLA components. The PLA sample's mean tensile strength was determined to be 17.772 MPa at 25% filler density, rising to 21.052 MPa at 50% and 28.723 MPa at 75%, peaking at 50.073 MPa at 100%. These findings indicated that the tensile strength of the PLA sample produced by 3D printing technology exhibited an increase with increasing filler density. Furthermore, the tensile elongation of the PLA sample at the fracture point according to the filler density was determined to be 5.59%, 6.36%, 7.35% and 5.7% at 25%, 50%, 75% and 100% density, respectively. Furthermore, an increase in infill density resulted in a corresponding rise in elastic modulus, from 367 MPa to 400 MPa, 473 MPa, and ultimately to 969 MPa [31].

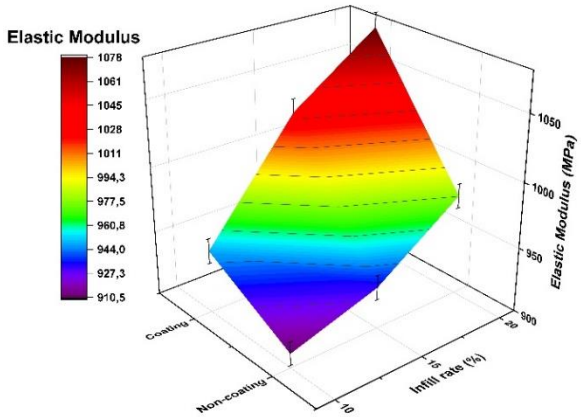

Figure 7. Elastic modulus

Chaćon et al. explored the impact of process parameters on the mechanical characteristics of PLA structures manufactured using FDM. The layering involved in the 3D printing process gives rise to anisotropic behaviour in the samples. As demonstrated in the study, the mechanical behaviours of components manufactured using disparate printing parameters manifested as maximum tensile strengths of 89.1 MPa and minimum tensile strengths of 20.2 MPa [27].

Pandzic et al. examined the impact of filler type and density on the tensile characteristics of PLA material in the FDM method. For the gyroid filler pattern, an increase in filler density from 10% to 90% resulted in enhanced ultimate tensile strength (UTS) for 50% and yield strength for 64%. At a filler density of 10%, the tensile strength of the part was 18.4 MPa, and at a filler density of 20%, it was 18.1 MPa. It was observed that all filler patterns exhibited maximum UTS and yield strength for 90% of the filler. The findings further demonstrate that the UTS of the PLA material with 100% filler is 42.15 MPa, and its yield strength is 36.40 MPa. A comparison of the UTS and yield strength of all filler patterns

with 90% filler and 100% filler reveals a discrepancy of approximately 40% [32].

In this study, the tensile strength of the coated PLA specimen produced at 20% filler density was determined to be lower than that of the PLA samples produced at 100% filler density, as reported in the existing literature. However, the tensile strength of the coated sample was higher than that of the PLA samples produced at the same filler density.

The results obtained demonstrate that the density of the infill exerts an impact on the modulus of elasticity values of 3D-printed PLA samples. It is evident that an augmentation in filler density results in enhancement of the elasticity modulus values of the 3D-printed PLA samples. Among the uncoated samples with varying filler densities, the specimen with a 20% filler density exhibited the highest modulus of elasticity, measuring 977.74 MPa. In the case of the coated specimens, the specimen with 20% filler density was determined to have the highest modulus of elasticity, measuring 1077.74 MPa.

The results also demonstrate the change in modulus of elasticity of uncoated and coated PLA samples at the same filler density. A comparison of the uncoated and coated samples at a 10% filler density reveals that the modulus of elasticity increases by 4.11% when the sample is coated. A similar trend was observed when the modulus of elasticity of uncoated and coated specimens with 15% and 20% filler densities was compared; the modulus of elasticity increased by 10.65% and 10.22%, respectively, when the specimen was coated. The highest modulus of elasticity (1077.74 MPa) was observed in the coated specimen with 20% filler density.

It is widely acknowledged within the relevant research community that the filler percentage is one of the most substantial parameters impacting the mechanical characteristics of the component. The results of the study indicate a clear correlation between an increase in filler percentage and an improvement in mechanical characteristics [6].

Abeykoon et al. researched the optimisation of FDM parameters for the purpose of enhancing PLA 3D-printed structures. For pure PLA, parts with 100% filler density achieved the highest modulus of elasticity of 1538.05 MPa. As is apparent from the findings, the modulus of elasticity of the sample exhibiting 100% filler density (1538.05 MPa) stands at about double the level of that observed in the specimen with 25% filler density (861.78 MPa). It has been documented that a reduction in filler density can result in an augmentation of voids within the structure, thereby precipitating a diminution in part strength. Filler density increases enhance mechanical bonding by decreasing porosity. Parts fabricated with a filler density of 100% exhibited the highest modulus of elasticity, and the strength of the printed parts decreased as the filler density decreased [33].

Tymrak et al. investigated the mechanical characteristics of parts manufactured utilising 3D printers under realistic environmental conditions. The results demonstrated that the mean tensile strength for PLA was 56.6 MPa, and the average elastic modulus for PLA was 3368 MPa [34].

In the current study, the elastic modulus of the coated PLA sample produced at 20% filler density was determined to be lower than that of the PLA samples produced at 100% filler density, as reported in the relevant literature. However, the modulus of elasticity was higher than the PLA samples produced at similar printing parameters such as the same filler density.

As illustrated in Figure 8, the fractured test specimens are presented for examination. The coated specimen with the highest filler density exhibited greater contact resistance against higher loads in comparison to the other samples.

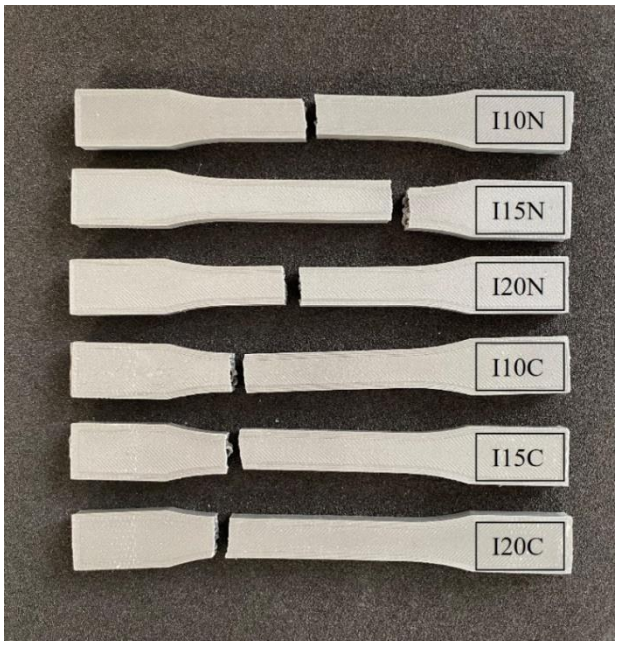

Figure 8. Fractured test specimens

The maximum hardness values attained as a consequence of the hardness (Shore D) test of uncoated 3D printed PLA samples produced at different filler densities and 3D printed PLA samples coated with micro silica reinforced epoxy are given in Figure 9.

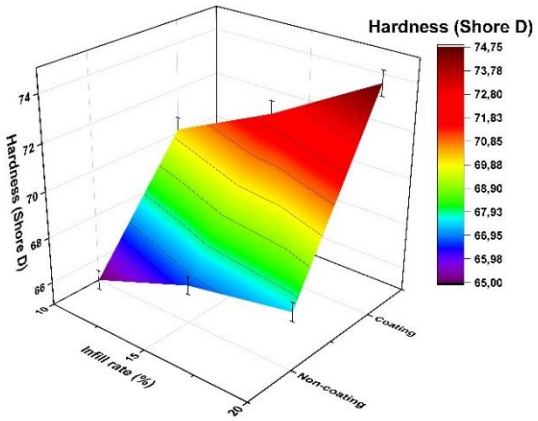

Figure 9. Hardness (Shore D) results

The findings indicate that the filler density has an effect on the hardness values of 3D-printed PLA samples. It is demonstrable that an increase in filler density results in a concurrent increase in the hardness values of the 3D-printed PLA specimens.

In the uncoated specimens, the maximum hardness value recorded was 67.5 Shore D, as observed in the specimen with a 20% filler density. Among the coated specimens, the highest recorded hardness value was found to be 74.7 Shore D, and this was observed in the sample with a 20% filler density.

The findings of the study demonstrate the variation in hardness values of uncoated and coated PLA specimens at a constant filler density. A comparison of uncoated and coated specimens at a 10% filler density reveals that the hardness value increases by 7.84% in the coated sample. A similar trend was observed when the uncoated samples with 15% and 20% filler density were compared with their coated counterparts, with an increase in hardness values of 8.4% and 10.66%, respectively. The coated specimen with a 20% filler density exhibited the highest hardness value of 74.7 Shore D among all the specimens. The coated specimen with the highest filler density exhibited higher hardness resistance in comparison to the other samples.

As demonstrated in the existing literature, an increase in filler density has been observed to correspond with an increase in hardness value. Furthermore, it has been ascertained that the hardness (Shore D) values of PLA specimens are subject to variation in accordance with divergent printing parameters.

An association has been identified between an increase in percentage filler density and a rise in Shore hardness values. This occurrence can be ascribed to the phenomenon of complete bond fusion of the material at the raster interface. Conversely, a decrease in the percentage of filler density ratio was determined to be associated with a decrease in Shore hardness values. The phenomenon under investigation may be attributed to the incomplete formation of bond fusion within the material at the interfaces [35].

Taha et al. conducted a study on the mechanical characteristics and build time of PLA 3D printed parts with linear patterns, differing thickness of the layer, build orientations and filler percentages. The hardness at different layer thicknesses (0.15-0.3-0.4 mm) at 10% filler density was in the range of 36.92-45.25 shore D, 32.79-48.24 shore D at 30% filler density, and 36.52-51.12 shore D at 50% filler density [36].

Hamoud et al. examined the effect of diverse filler patterns and print orientations on the mechanical characteristics and print time of PLA utilising FDM. The hardness measurements were recorded for various filler patterns and build orientations, including diagonal, triangular, and 3D diagonal filling patterns, as well as flat orientations. The findings indicated that the hardness measurements ranged from 45.8 to 46.5 at a 25% filling rate, from 45.8 to 47 at a 50% filling density, and from 46 to 47.1 shore D at a 75% filling density [37].

Maguluri et al. researched the affect of printing parameters on the hardness of 3D-printed PLA parts. To do this, they used the DOE approach. The study established that the hardness (Shore D) of the 3D-printed PLA parts varied markedly with different printing parameters, including varying speeds, nozzle temperatures, and filler densities. The Shore D hardness values ranged from 75.58 to 80.27 at 50% filler density, from 78.34 to 83.46 at 75% filler density, and from 79.27 to 84.34 at 100% filler density [38].

Dakhil et al. undertook research into the influence of filling pattern and filling ratio on the compressive strength and hardness of 3D-printed PLA polymers. The Type D Shore Durometer hardness results generally ranged from 67 to 85, with an average hardness value of 81.37 Shore D [39].

In the study undertaken by Hanon et al., the influence of three-dimensional printing parameters on the mechanical characteristics of PLA polymer was investigated, with a particular focus on the correlation between these parameters and the resulting hardness. The investigation revealed that samples produced at 100% filler density exhibited hardness values ranging from 78 to 81 Shore D [40].

In the present study, the Shore D hardness value of the uncoated PLA sample produced at 20% filler density was determined to be lower than the PLA samples produced at 100% filler density in the studies referenced in the literature. However, the hardness (Shore D) values were higher than the PLA specimens produced at similar printing parameters, such as the same filler density. Furthermore, the hardness (Shore D) values of the coated PLA specimens were higher than those of the PLA samples produced under similar conditions documented in the extant literature. This can be ascribed to the formation of a harder layer on the surface of the PLA samples by the micro silica-reinforced epoxy coating, thus increasing the Shore D hardness.

This method facilitates the fabrication of more strength and hard parts and components with high wear resistance, particularly in the automotive industry. Moreover, in the aerospace industry, the utilisation of lightweight yet robust materials confers distinct advantages for components that are critical in supporting structural loads.

4 Conclusion

The findings derived from the investigation into the impact of incorporating micro silica-reinforced epoxy into the 3D-printed PLA materials during the dip coating process on the mechanical properties are presented in below.

- The enhancement of filler density resulted in a substantial augmentation in tensile strength and elasticity modulus values of the 3D-printed PLA components.
- Among the uncoated specimens with different filler densities, it was determined that the specimen with 20% filler density had the highest tensile strength among the uncoated specimens with 20.43 MPa.
- The coated specimen with a 20% filler density was determined to have the highest tensile strength of 22.34 MPa and the highest elasticity modulus value of 1077.74 MPa among all specimens.
- The investigation revealed that the coated sample with a 20% filler density exhibited the highest hardness value of 74.7 Shore D among all the samples examined.

Conflict of interest

The author declares that there are no conflicts of interest.

Similarity rate (iThenticate): %18

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