Effects of a New Filling Technique on the Mechanical Properties of ABS Specimens Manufactured by Fused Deposition Modeling

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Abstract

No one can deny the widespread of 3D printing in many different fields. This paper aims to improve the mechanical properties of parts printed by fused deposition modeling (FDM) technique. Acrylonitrile butadiene styrene (ABS) specimens are printed with custom printing parameters, these parameters give a tensile strength that is 86% of the injection molded ABS strength, and give one of the best results recorded for 100% infill printed ABS tensile specimens. Furthermore, a post filling technique has been studied, specimens are printed with inner voids and different densities using slicing software. Void shape is precisely selected to conform to the filling process. High-strength low-cost thermoset resin is injected through specimens to fill these voids. A tensile test has been performed after full curing of the resin and a morphology analysis is done. By this technique strength to printed weight ratio is improved by 151% and the cost is reduced by 51%.

1 Introduction

Additive Manufacturing (AM) is the best choice to fulfill the fourth industrial revolution, as it delivers complex and customized products with great freedom in design in a very short time, reducing the production cost and shortening the development cycle[1]. Stereo-lithography (SLA) is the first technique that AM had started with, which is a liquid-based raw material technique. Later on, many techniques had been invented varying in the raw material from liquid to powder and solid[2]. All AM techniques use three-dimensional computer-aided designs (CAD) to produce –layer by layer– three-dimensional products by selectively adding materials, with variety in the materials being used. FDM, solid-based AM technique, is the most common and widely used technique due to its simplicity and modesty in price as it utilizes low-cost polymers only[2, 3]. FDM feeds thermoplastic filament into a heating chamber until it reaches a semi-liquid state, extrudes it through a nozzle above its melting point, then depositing it on the printing platform in specified positions according to the G-code generated by the machine's software[4]. FDM printed parts have been in use in many fields like rapid prototyping, building, healthcare devices and tools, motor drives, and aerospace components[5]. But due to the nature of the FDM technique, it experiences some drawbacks; one of them is the limitation in mechanical properties. This limitation is due to the weak and non-homogenous bonding between the corresponding layers building up the part and also between the roads building the layer itself. Also since the cooling and heating rates in the FDM process are unstable there would be uncontrolled shrink and defects in the microstructure[2, 6].

Many studies had been performed to overcome the pre-mentioned problems, covering different materials that are currently used in FDM (ABS, PLA, PA, NYLON, etc.). Many studies have considered printing parameters as important indices for product quality. They studied the influence of printing orientation, speed, raster angle, infill pattern, nozzle temperature and layer height on the mechanical properties of the printed parts[7, 8]. Table 1, summaries the studies done by researchers on 3D printed ABS parts applying different printing parameters.

Table 1
Previous work on ABS printed specimens

Authors	Parameters and (levels)	Outputs
Samykano et al. [9]	Printing speed (30 mm/s), printing temperature (220°C), bed temperature (110°C), infill pattern (lines), layer height (0.35, 0.4, and 0.5 mm) and raster angle (45°, 55°, 65°).	σ_t E_t Toughness
Rangisetty et al. [10]	Layer height (0.2 mm), extruder temperature (240°C), bed temperature (90°C), print speed (55 mm/s) and infill pattern (line, Concentric, Triangular, and Honeycomb).	σ_t E_t σ_f E_f
Bamiduro et al. [11]	Orientation (0°/90°, -45°/45°)	σ_t
Meng et al. [6]	Layer height (0.1 mm), orientation (vertical, ,horizontal) ,printing speed (40 mm/s), extruder temperature (235°C), bed temperature (80°C), composition (ABS,ABS/SiO_2, ABS/MMT, ABS/MWCNTs, ABS/$CaCO_3$)	σ_t σ_f E_f
Coogan et al. [12]	Bed temperature (100°C, 125°C, 150°C), print speed (1000, 2000, 4000) mm/min, layer height (0.15,0.3,0.45 mm), nozzle temperature (230 °C, 255°C, 280°C), fiber width (0.4, 0.6, 0.8 mm)	Bond strength Longitudinal strength
Huang et al.[13]	Layer thickness(0.1, 0.2, 0.3 mm), raster angle (45°/-45°,30°/-60°,0°/90°), printing speed (20, 40, 60 mm/s), building orientation (horizontal, lateral, vertical), bed temperature (80°C), printing temperature (235°C)	σ_t σ_f Impact strength
Koch et al. [14]	Print temperature (250°C), bed temperature (210°C), layer height (0.2 mm), raster angle (0°,-45°/45°,90°), travel speed (2000 mm/min), solidity ratio (0.6-1)	σ_t
Cantrell et al. [15]	Layer height (0.1 mm), printing temperature (235°C), bed temperature (105°C), orientation (Horizontal, lateral, vertical), raster angle (-45°/45°,0°/90°, 30°/-60°,15°/-75°)	σ_t

Authors	Parameters and (levels)	Outputs
Rayegani and. Onwubolu [16]	Orientation (0 ° ,90 °), raster angle (0 ° ,45 °), raster width (0.2032,0.558 mm), air gap (0.558,−0.00254 mm)	σ_t

Other studies adopted the potential of improving physical and mechanical properties of the raw material itself. Nanoparticles were prepared and mixed with the printing filament to produce a new one[6, 17–19]. Some research focuses on improving the overall mechanical properties of the 3D printed part by decreasing its anisotropy or increasing its isotropic behavior[20, 21].They replaced the thermoplastic polymers that results in poor chemical and thermal properties by two-component epoxy resin[20],epoxy resin poses good chemical and physical properties and gives high-strength bonding, with light weight structures withstanding high static loads[22, 23]. Filippova et al. [21] impregnated ABS 3D printed samples in epoxy resin compound with different hardeners. 142% and 133% were achieved as an improvement in ultimate tensile strength depending on the hardener type. Instead of impregnation, Belter and Dollar [24] injected epoxy resin through ABS flexural specimens. This results in improving the overall part stiffness and strength by up to 25% and 45% respectively. Moreover, Jiang et al. [20] used epoxy as the main raw material in FDM technique to get the best use of its mechanical properties and print products can be used in harsh conditions. Tensile specimens were printed of a mixture of only epoxy and CNT giving a tensile strength of 55 MPa.

In this paper, ABS tensile specimens are printed with printing parameters based on the survey presented in Table1. A comparison between the results of many previous studies is held to decide on the best parameters to print with. Also using these printing parameters, another tensile specimens are printed to test a new filling technique. This technique is a post processing technique aims to improve the mechanical properties, reduce cost and weight. Hence the parts are printed with inner voids which reduces the part weight, time and cost of printing in turn. Then these voids are injected with low-cost, less dense resin which poses higher mechanical properties. To make the part sparse inside, voids could be designed and located precisely during design stage by CAD software, or slicing software manage these process through infill density parameter [25]. In this study, the parts are sparse by slicing software, three infill density are printed (20%, 40% and 60%) and injected by epoxy resin that is less in price by 91%. The infill pattern chosen is gyroid pattern to let the resin to spread entire the whole part. Tensile tests and morphology analysis are performed to investigate the improvement of this technique.

2 Experimental

2.1 Materials and samples

In this study, ABS (Acrylonitrile butadiene styrene) had been used as filament material, it was obtained from (AMTech 3D Printing company, Cairo, Egypt) with a diameter of 2.85 mm, density of 1.1g cm^{-3}, and metal flow index of 41g/10min. Deco-pox 039 epoxy resin was obtained from (Pioneers for Polymers &

Chemicals PPC company, Alexandria, Egypt). The resin has a bisphenol-A base, and the hardener has polyamine one [26], Table 2 shows the resin properties.

Table 2
Physical and chemical properties for Deco-pox039

Property	Resin	Hardener
Boiling point/Boiling range	>200 °C	>200 °C
Flash point	>150°C	>100°C
Density at 23°C	appr. 1.1 g cm^{-3}	appr. 1.03g cm^{-3}
Viscosity **dynamic at 23**°C	appr. 1000 mPa.s	appr. 190 mPa.s
Density of the mixture at 23°C	1.1 g cm^{-3}	

Tensile specimens were designed according to ASTM638 type I [27], and printed on ultimaker [3] with nozzle diameter 0.4 mm and Cura 4.8 slicing software in ideaspace company as shown in (Fig. 1).

2.2 Methodology

2.2.1 Printing 100% infill specimens

In this study 100% infill ABS tensile specimens were printed with printing parameters that were precisely selected based on the literature in Table 1, the selected parameters are believed to give the best results as it were selected based on the previous experimental work done on this material regarding the results obtained in every study. Table 3 summaries the parameters used in the present study. After printing, tensile test was performed, all tensile tests in this research had been performed on German Zwick testing machine Z010.

Table 3
Printing parameters for ABS

Printing temperature	**240°C**
Printing speed	40 mm s^{-1}
Layer thickness	0.2 mm
Build plate temperature	100°C
Printing orientation	Horizontal
Raster angle	0 °
Infill pattern	Lines

2.2.2 Filling technique

In this technique, tensile specimens had been printed with inner voids to be injected with epoxy resin, ABS specimens were sparse inside using the slicing software. The software controls how dense the part is by infill percentage parameter, three percentages had been printed 20%, 40%, and 60% with a pattern that allowed the resin to flow through the whole specimen, and two holes of 0.4 mm for injection and venting were drilled in the specimens (Fig. 2).

To identify the mechanical properties of the epoxy resin being used, tensile test had been done on deco-Pox039 Epoxy resin, two components A and B were mixed together under the predefined percentages, then the mix was poured into a custom-made silicone rubber mold in (Fig. 3a) and let for 7 days to fulfill the full curing as written in the product data sheet, the test was done following ASTM638 type I.

After testing the epoxy specimen and making sure about its properties, it was approved to be used as an injection material. Epoxy injection within the ABS printed tensile was done using a syringe, the syringe was immersed inside the specimen trough one of the holes and sealed very well, and the other hole was for venting. The syringe used was G16 to conform to the highly viscous epoxy. Injection process was in vertical orientation, syringe was immersed at the bottom and the direction of injection was against gravity to make sure the epoxy filled the whole specimen by reaching the top, (Fig. 4) shows the direction of injection. (Fig. 5) represents sections at different locations in a specimen to ensure epoxy flowed through the whole specimen. Tensile test was done –after seven days from specimens injection, the full curing time– on German Zwick testing machine Z010, with 10 KN calibrated load cell, and crosshead speed of 5 mm min^{-1}. At least three samples for each case were tested. Morphology analysis on the fractured specimens had been done, as the fracture surfaces were observed via scanning electron microscope (SEM, JEOL JSM_5400LV). All the surfaces were gold-sputtered before observation and the observation was at an acceleration voltage of 15 KV.

3 Results And Discussion

3.1 Results of Epoxy resin test

The mechanical behavior of deco-Pox039 Epoxy resin is shown in (Fig. 6), the tensile test had been done on four specimens to take the average and give the best accurate result. The epoxy used in this paper have a resin of Aromatic bisphenol (bisphenol-A) and hardener of amino methylamine and phenyl methylamine. And the ultimate tensile strength obtained was 44.8MPa and elongation at break was of 12%. This result is higher than the tensile strength obtained by Filippova et al[21],and it is related to the chemical composition hence the hardeners tested by Filippova et al. were triethylenetetramine (TETA) and polyethylene polyamine (PEPA) which resulted in tensile strength of 22.4 MPa and 22.7 MPa respectively. On the other hand, Halder et al[28],used a resin of bisphenol-A and amine-based hardener so their results was very close to the results in this paper as they recorded 41.92 MPa as best tensile strength. K. Agarwal and G. Agarwal [29],had tested the bisphenol-A resin with two different hardener types: triethylenetetramine (TETA) and diaminodiphenyl methane (DDM) giving a strength of 52 MPa and 83 MPa respectively. And when using bisphenol-F as a resin with aromatic amine hardener the strength reached 84 MPa [30].

3.2 Results of 100% infill ABS test

(Fig. 7), represents the result of the tensile test on 100% infill printed ABS specimens with the parameters in Table 3, three specimens were tested, elongation at break was 7.4% and tensile strength was 36.3 MPa. This result is considered one of the best result obtained for 100% infill ABS tensile specimens. (Fig. 8), shows a comparison between the result of the present study, and most of the results obtained in the studies mentioned in Table 1, the variation in results ensures the influence of printing parameters on the mechanical properties of the printed part. Table 4 compares the printing parameters used in the present study to those used by T. Coogan et al.[12] as they got the nearest result to this study's result. Both of the two studies have very close parameters, the main difference is in layer height parameter as 0.2mm layer height that is adopted in this research is believed to be the best height fulfilling the best boding between adjacent roads and consecutive layers

[31, 32].

Table 4. Comparison between printing parameters in the present study and in the nearest paper to this paper's result

	Present study (tensile strength: 36.3 MPa)	**T. Coogan et al [12] (tensile strength: 34.5 MPa)**
Printing Temperature	240°C	280°C
Bed Temperature	100°C	125°C
Printing Speed	40 mm s^{-1}	2000 mm min^{-1} $\cong$ 33.33 mm s^{-1}
Layer Height	0.2 mm	0.3 mm
Pattern	Lines	Lines
Raster Angle	0 °	0 °

3.3 Results of filling ABS test

The effect of Epoxy resin injection within ABS printed part is represented in (Fig. 9), all printing parameters, injection material and method were controlled, the variables were infill density of ABS while printing and the injected volume of epoxy in turn.

Apparently, the results are very close, average tensile strength for 20% ABS infill-80% epoxy injection (**20B-80E**) is 24.77MPa, for 40% ABS infill-60% epoxy injection (**40B-60E**) is 27.03MPa and 21.8MPa for 60% ABS infill-40% epoxy injection (**60B-40E**). Although the strength of 40% infill is marked the best but by analyzing the weight and corresponding printing time, (**20B-80E**) gives the optimum strength to printed weight ratio Table 5. Furthermore, the preference of 20% infill ABS injected with epoxy to the pure 100% infill printed ABS was investigated, and it was concluded that by reducing 56% of the part weight -in 20% infill-, the product mechanical strength reaches 68% of the printed part with 100% infill, and the strength to printed weight ratio is increased by 151%, Table 5. Strength to printed weight ratio is analyzed in this study rather than the common strength to weight ratio; because the injected epoxy resin has the same density of ABS filament used -1.1 g cm^{-3} -. Some others thermoplastic filament material like PLA which poses higher density (1.17-1.24 g cm^{-3}) [8] might show better results when injected with similar epoxy types. Results of the previous tests indicate adequate adhesion between epoxy and ABS. Since the effective surface is considered the main parameter to give best adhesion, and one of the techniques to enhance the effective surface is roughening it but to an acceptable level. -As if the surface is more rough the adhesion stress would decrease-[33]. And hence one of the themes of FDM process is the moderate surface finish, so that would fulfill good adhesion between epoxy and ABS. (Fig. 10), represents sections in 20%, 40% and 60% infill specimens after injection and testing.

Table 5
Physical and mechanical properties obtained from ABS test

	Ultimate tensile strength (MPa)	**Strain at ultimate strength (%)**	**Printing time**	**Printed weight (g)**	**Printed weight reduction (100%)**	**Strength/printed weight ratio**	**Specimen weight (g)**
100% ABS infill	36.30	7.40	1h 36m	16	0%	2.32	16
20% ABS infill	24.77	6.27	59m	7	56.25%	3.50	16
40% ABS infill	27.03	6	1h 8m	9	43.75%	3	16
60% ABS infill	21.80	7.20	1h 29m	12	25%	1.80	16

4 Morphology Analysis

Results for morphology analysis are shown in (Fig. 11), it illustrates the bonding between the adjacent roads of ABS filament in the same layer, and shows the bonding between the consecutive ABS layers. The first remark is that roads cross-sections are not circular anymore and that due to the compression induced from the layers on each others. The bonding between adjacent roads is on more than 50% of its height, when notice the lines in (Fig. 11a), it could be concluded that the bonding height is between 90 and 170 microns. The gaps between consecutive layers are represented by lines in (Fig. 11b) and the gap height is between 18 to 21 microns. The trans-granular cleavage shown in each road cross-section indicates the brittle fracture mode of the material, (Fig. 11c).

(Fig. 12), shows SEM micrographs of an overview for three sections in (**20B-80E**), (**40B-60E**) and (**60B-40E**) specimens (a, b and c) respectively. In the micrographs of the injected ABS specimens the contact surfaces between epoxy and ABS could be marked indicating super adhesion. Small discrete surface areas inside ABS specimens that were designed by printing software, helped to make it fully composite as the epoxy was immersed through the whole part. (Fig. 13), representing the three coated sections before being examined in the microscope.

By going deep in (**20B-80E**) specimen (Fig. 14), there are three levels of the ABS road as the mechanical fracture leaves unpaved surface in (Fig. 14b), in (Fig. 14c) there is perfect bond between epoxy and ABS with a vital defect in epoxy resin mix indicated some air bubbles, (Fig. 14d) and (Fig. 14e) indicates different levels of fracture in both epoxy and ABS with beach marks to ensure the brittle fracture and more air bubbles appear.

The same phenomena were recognized in (Fig. 15) and (Fig. 16) representing (**40B-60E**) and (**60B-40E**) specimens respectively. In (Fig. 15b) is a magnified image of (Fig. 15a) where the brittle fracture is obvious and also it refers to discontinuity in injection. (Fig. 15d) is a magnified image of (Fig. 15c) and it shows 50 and 35 micron air bubbles in Epoxy mix. In (Fig. 16a) representing the fracture, it was just before a relative large air bubble and also there is another one that was collapsed by the fracture, (Fig. 16b) represents epoxy that is covering some sheared filaments.

5 Conclusion

- Printing parameters highly affect the mechanical properties of the printed part, printing parameters used in the present study is highly recommended as it gave one of the best results obtained for ultimate tensile strength of -36.3 MPa-.
- The presented injection filling technique, could be considered a promising technique; as it reduces the printing time and cost aiming to sparse the part, these spares are filled simply and easily with a low-cost material and the overall result is improving the strength to printed weight ratio. This improvement was by 151% in case of (**20B-80E**) specimens and 129% in case of (**40B-60E**) specimens, but in case of (**60B-40E**) there was not any improvement and that mainly because of the relative low volume of injected epoxy within these specimens.
- Injection filling technique is a post process technique and it could follow any 3D printing process not only FDM.
- Epoxy resin as a filling material was a good choice due to its higher toughness and tensile strength. 1 gram of Deco-pox039 resin injected within ABS specimens is lower in price than 1 gram of printed ABS by 91%. However, epoxy resin has many types so the best selection would became after studying the physical, chemical and mechanical properties needed.
- The denser and more discrete the voids are, the best adhesion between epoxy and the printed part.
- Epoxy resin mixture should be vacuumed before injection and also the printed part should be degassed while injection to avoid air bubbles induction.
- The presented filling technique could show more potential, the less the injected material is in density and the higher it is in mechanical properties in comparison with the thermoplastic printed material.
- The presented filling technique could show high potential in various application which requires light structures. Hence the trend in racing cars in Formula is to lighten the car weight, and replacing the metal parts by lightweight printed plastic ones, this technique could applied to reinforce these parts [1]. Also the strength-to-weight ratio is considered a vital concept in aerospace industry, as adding 100 Kg of weight can increase the expense of an airline to come over $2.5 million in fuel over an aircraft’s lifetime. The filling technique could improve the properties of AM components that have been immersed in this industry significantly[1]. And finally, in cultural preserving field historical monuments are being scanned to print identical ones putting them in exhibitions or shops[5]. The presented technique could not only reduce the cost but also it could take the mechanical properties of the printed parts to a high level.

Abbreviations

σ_t Tensile strength

σ_f Flexural strength

E_t Elastic modulus

E_f Flexural modulus

Declarations

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Competing Interests

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Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection were performed by [Heba Hussam]. Data analysis was performed by [Heba Hussam] and [Yasser Abdelrhman].The first draft of the manuscript was written by [Heba Hussam]. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Figures

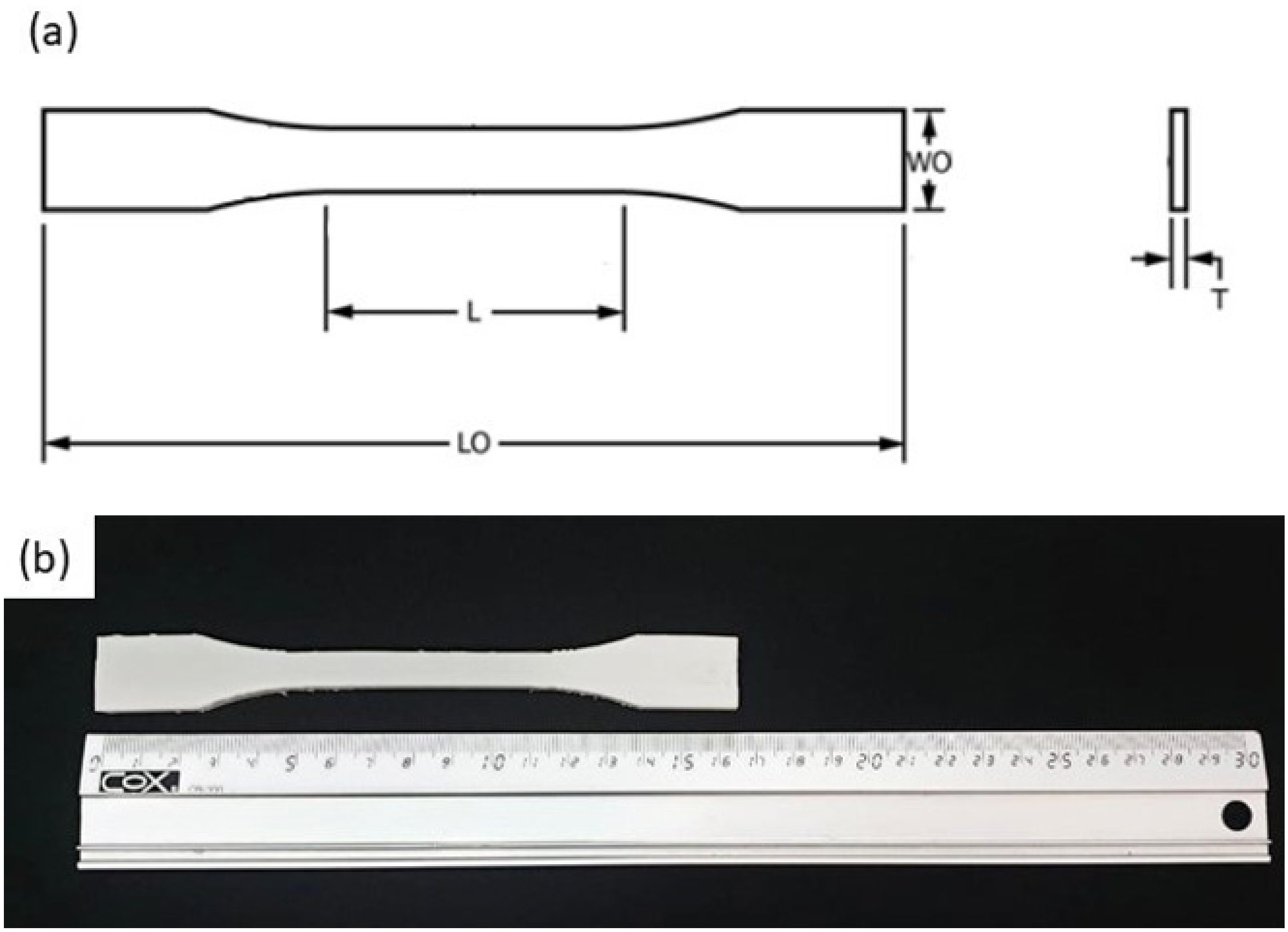

Figure 1

Specimen geometry according to ASTM D638 standard (**a**), printed tensile specimen (**b**)

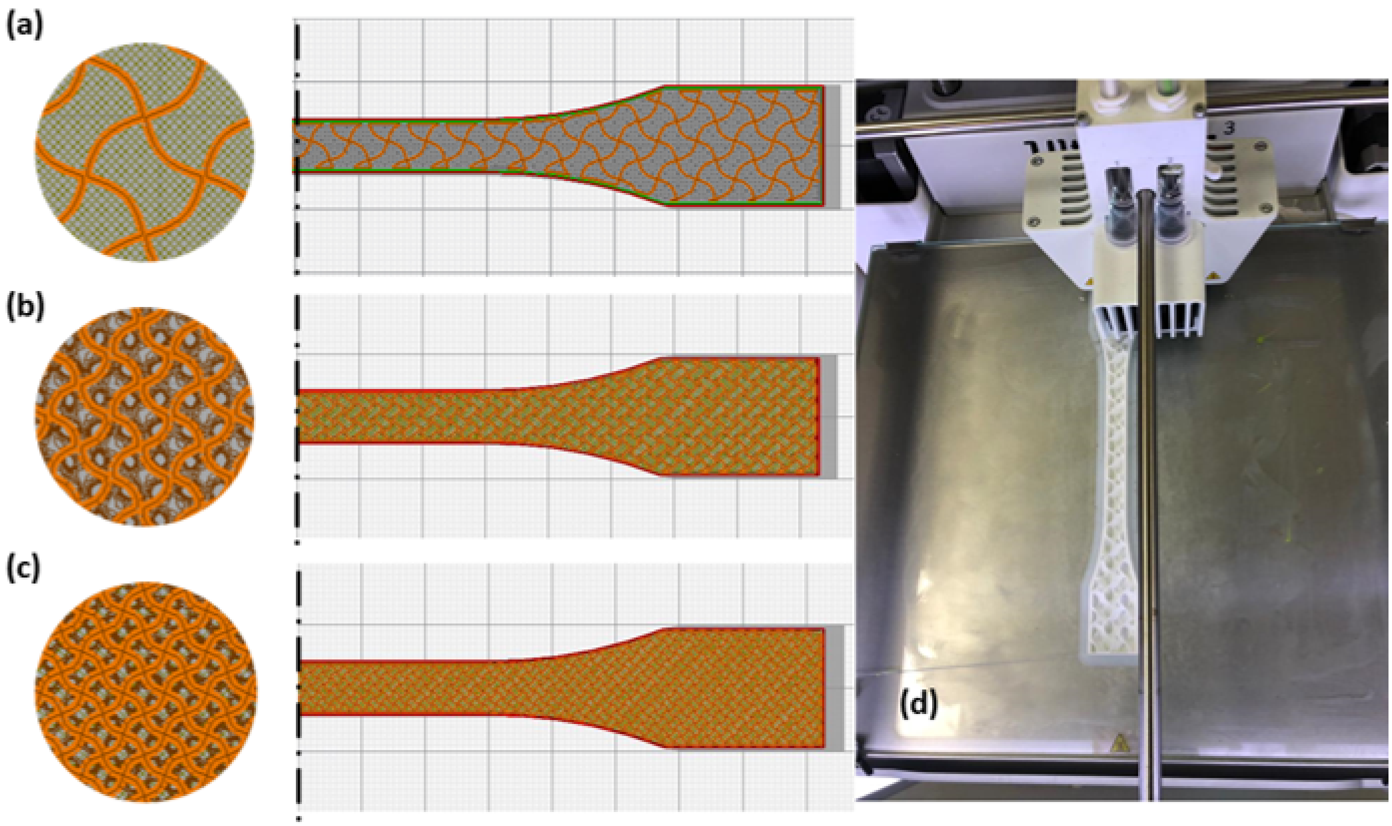

Figure 2

20% infill ABS tensile specimen (**a**), 40% infill ABS tensile specimen (**b**), 60% infill ABS tensile specimen (c), and 20% infill ABS specimen while printing on Ultimaker[3] (**d**)

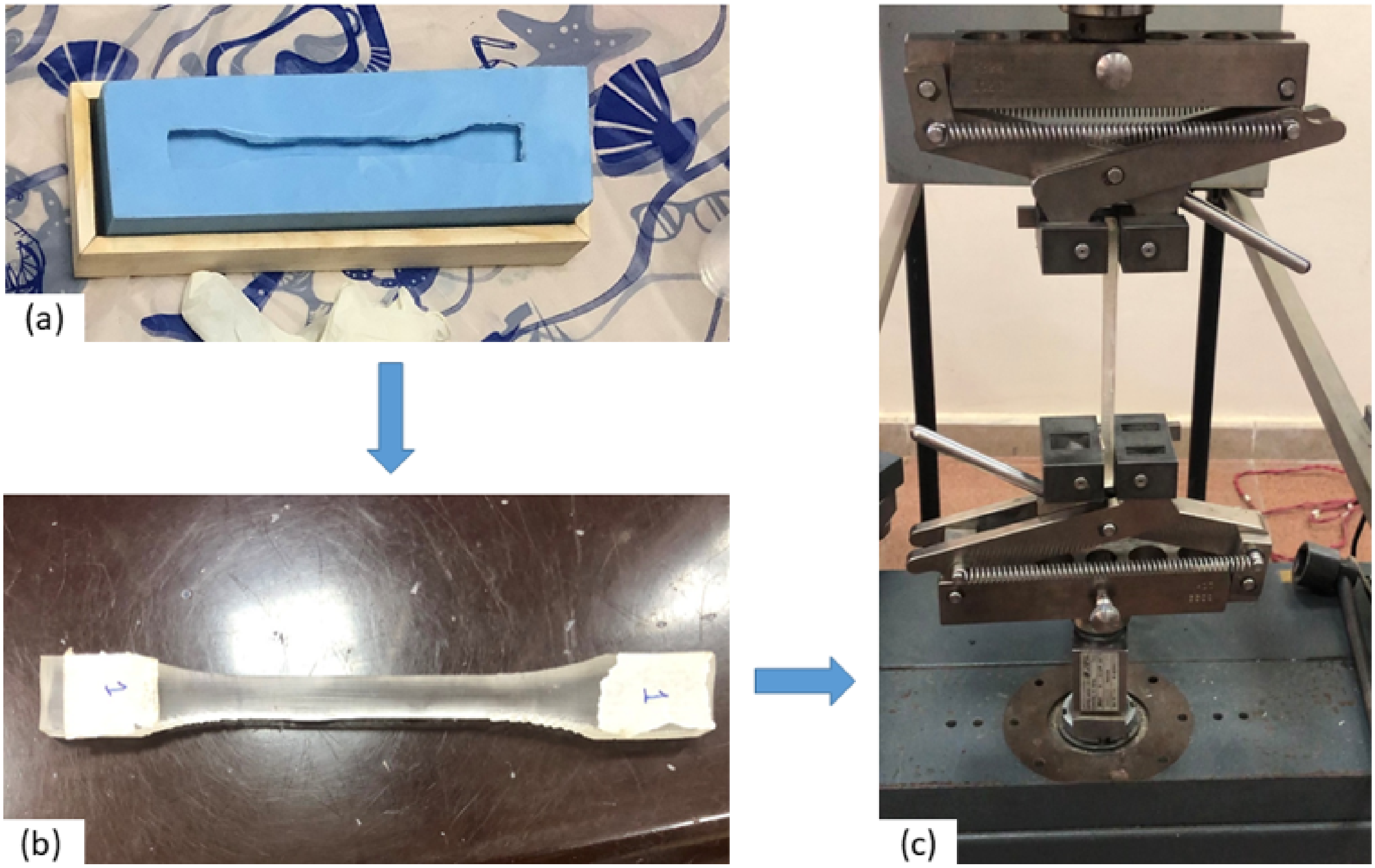

Figure 3

Silicon mold for casting epoxy (**a**), casted epoxy tensile specimen (**b**), and epoxy specimen during testing (**c**)

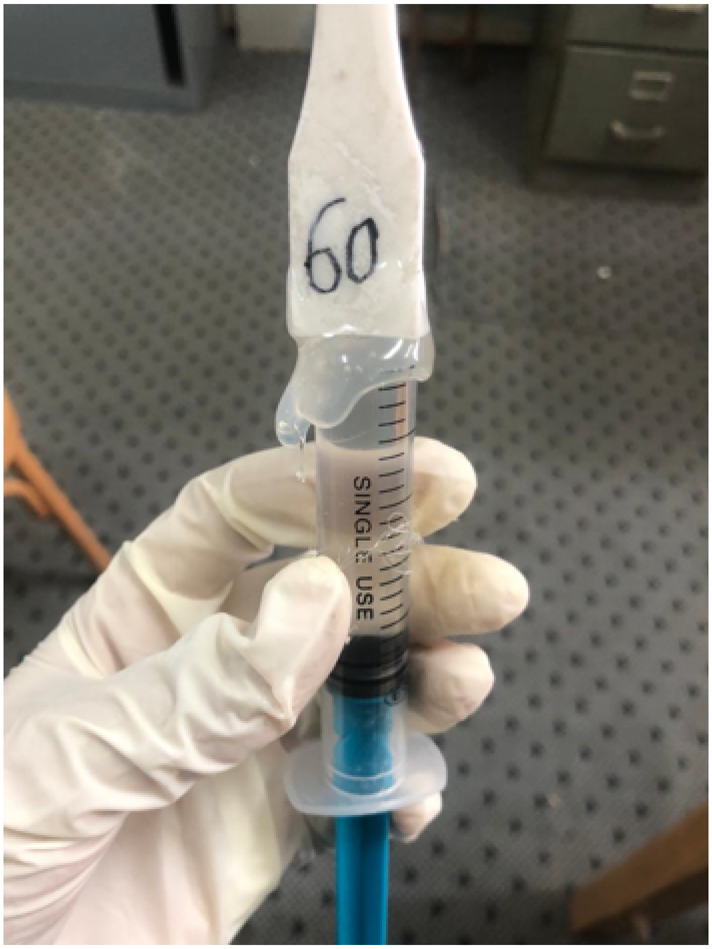

Figure 4

Injection process of 60% infill tensile specimen

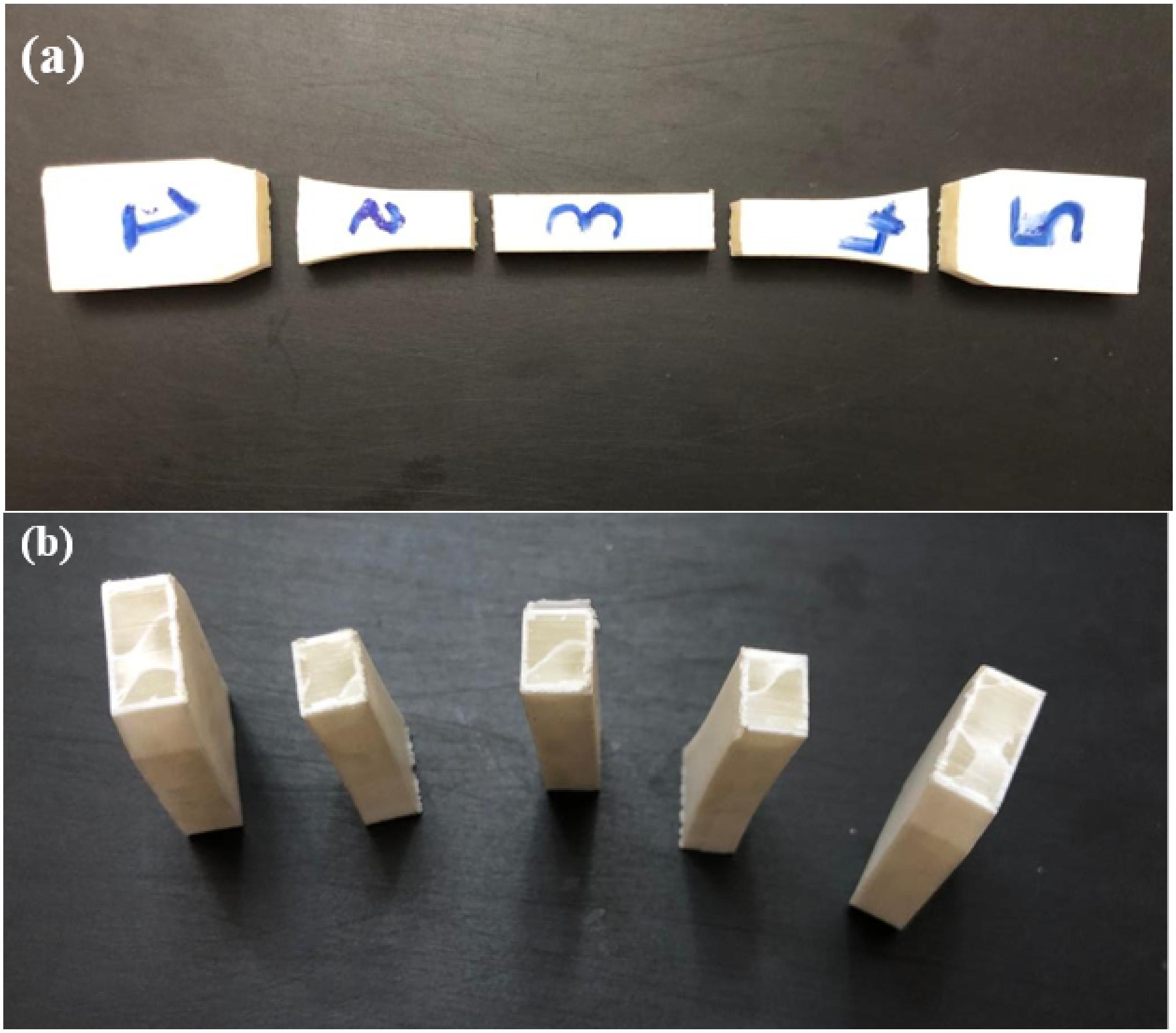

Figure 5

Sections in injected tensile specimen (**a**), top view of the sections (**b**)

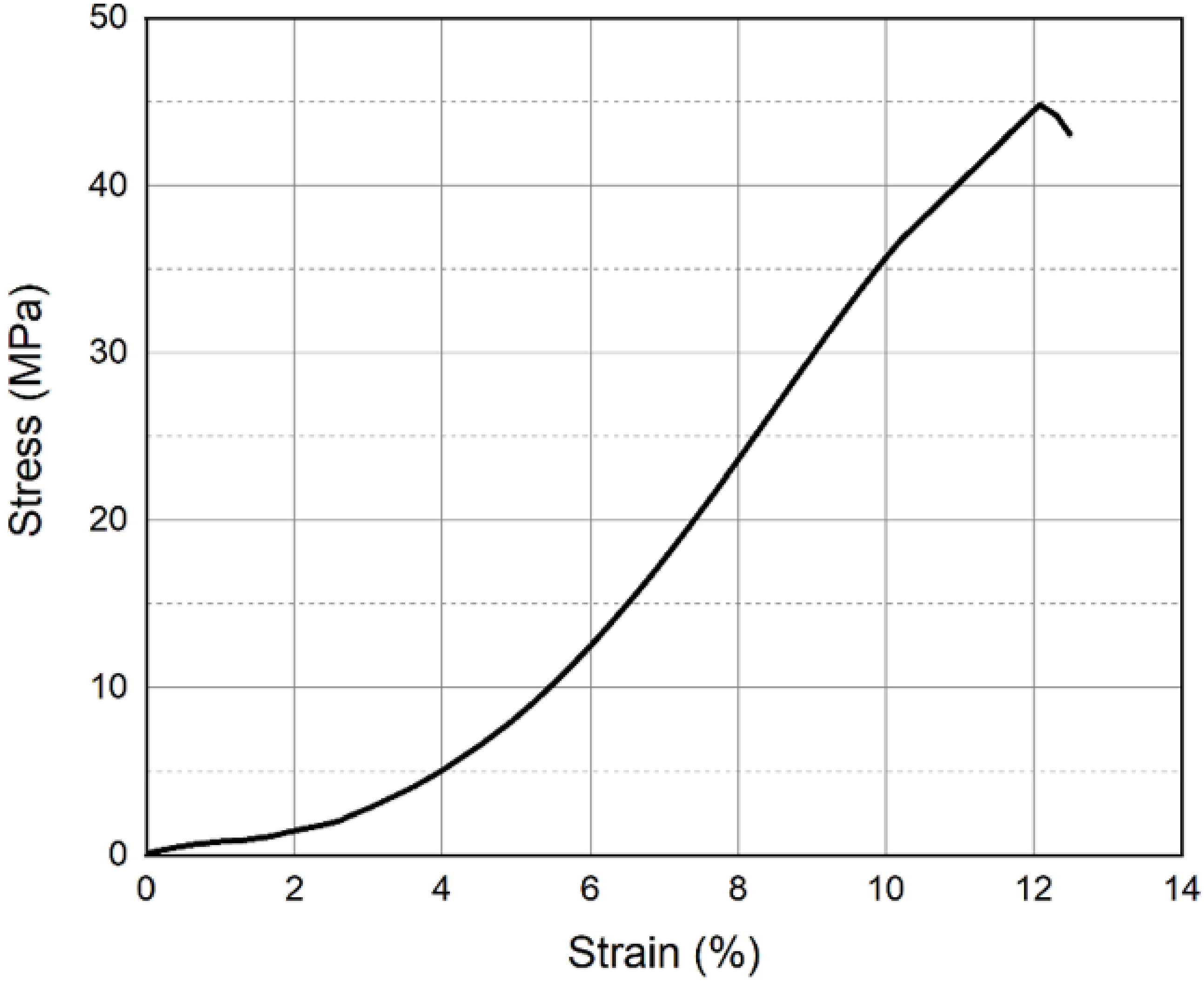

Figure 6

Deco-pox039 average tensile test result

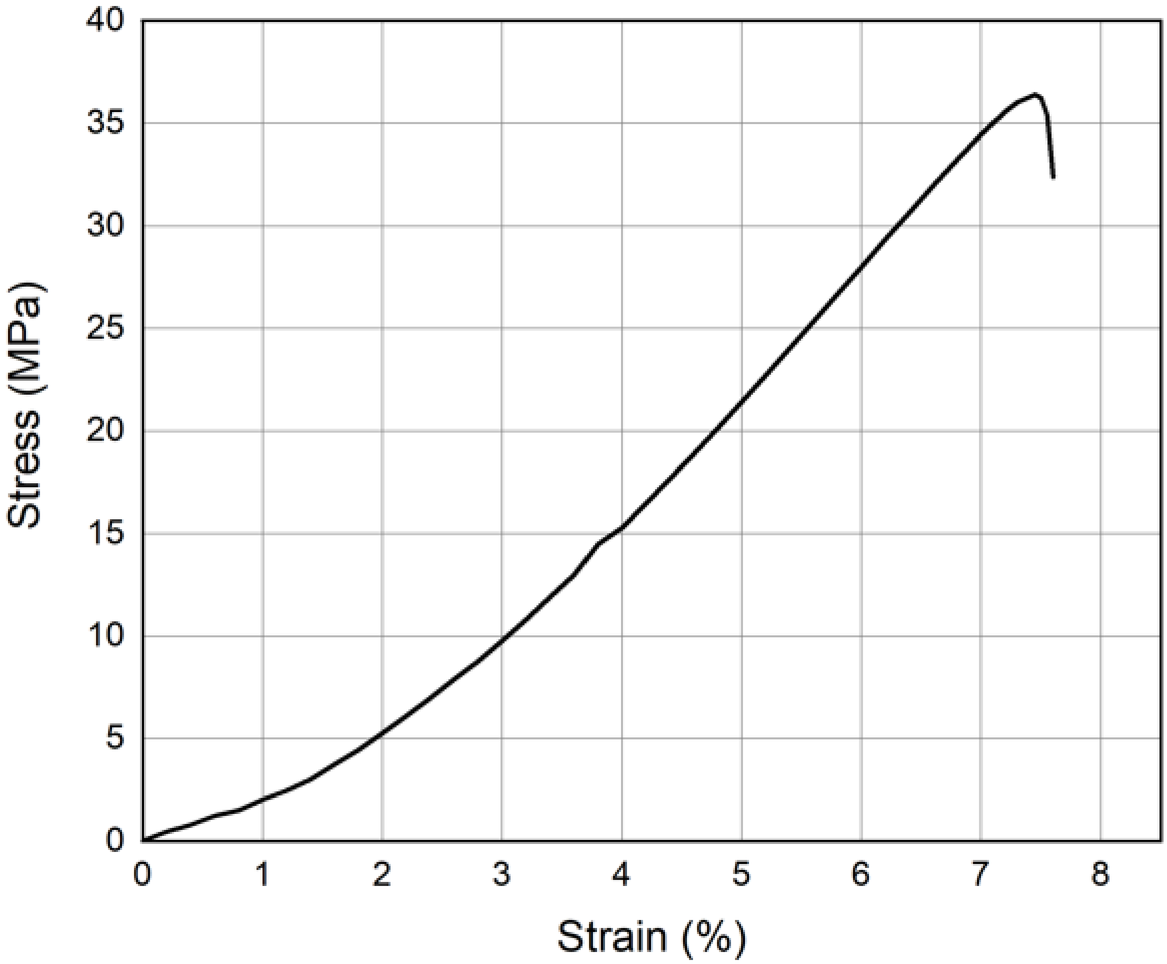

Figure 7

Results of ABS 100% infill tensile test

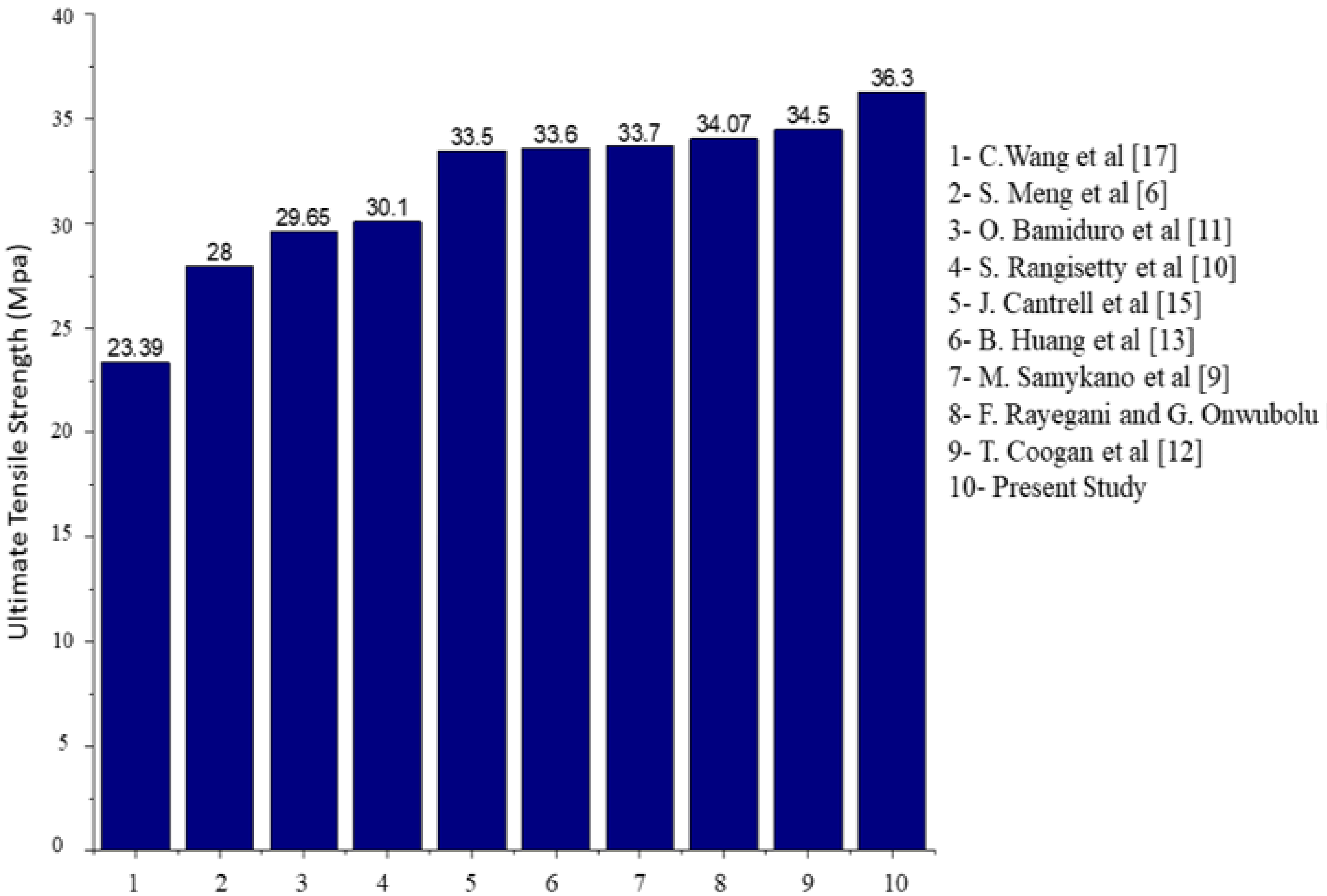

Figure 8

Tensile strength values reported by other researchers for 100% infill ABS compared with the obtained one by present study

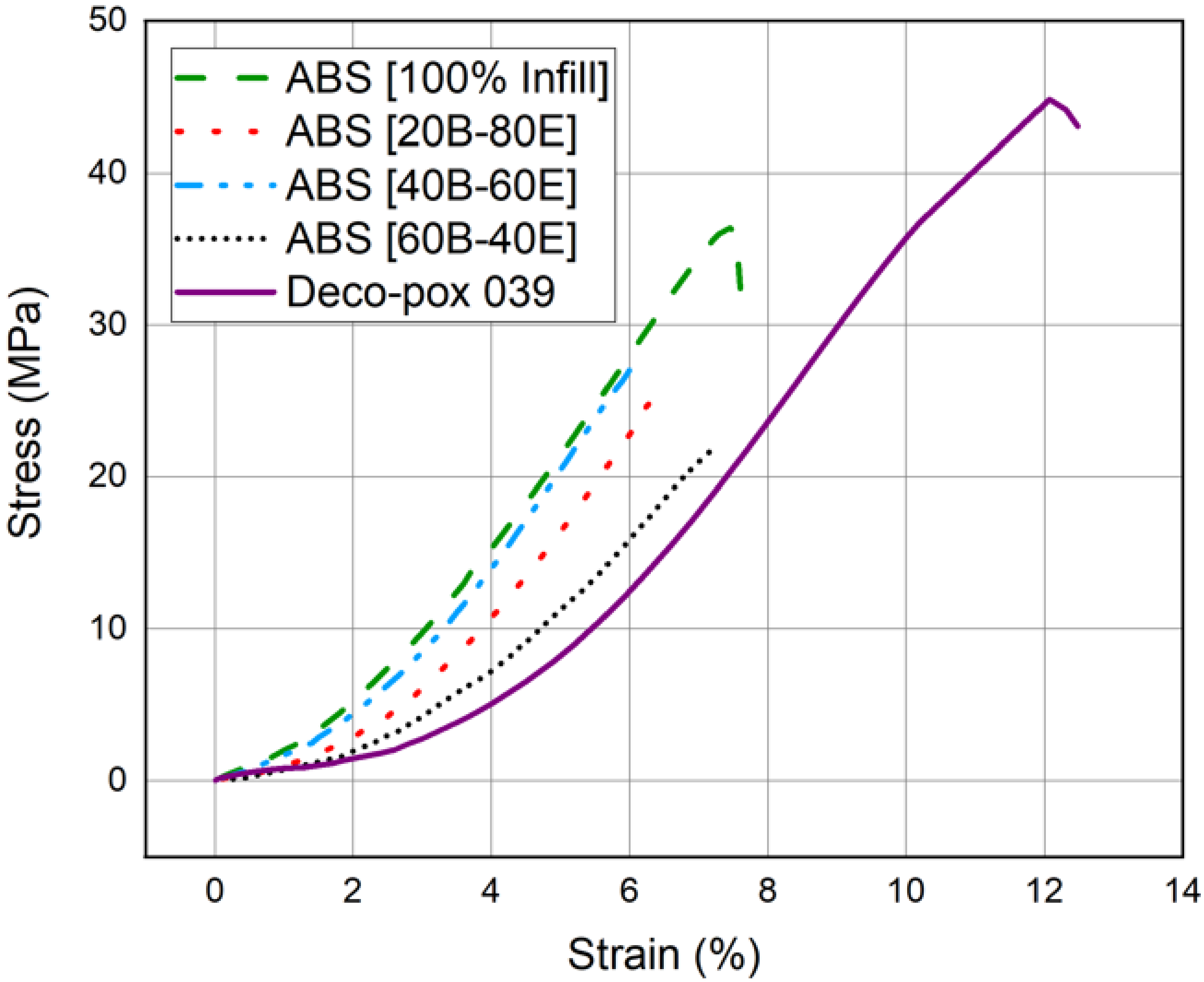

Figure 9

Results of composition technique in 20%, 40% and 60% infill in comparison with 100% ABS infill

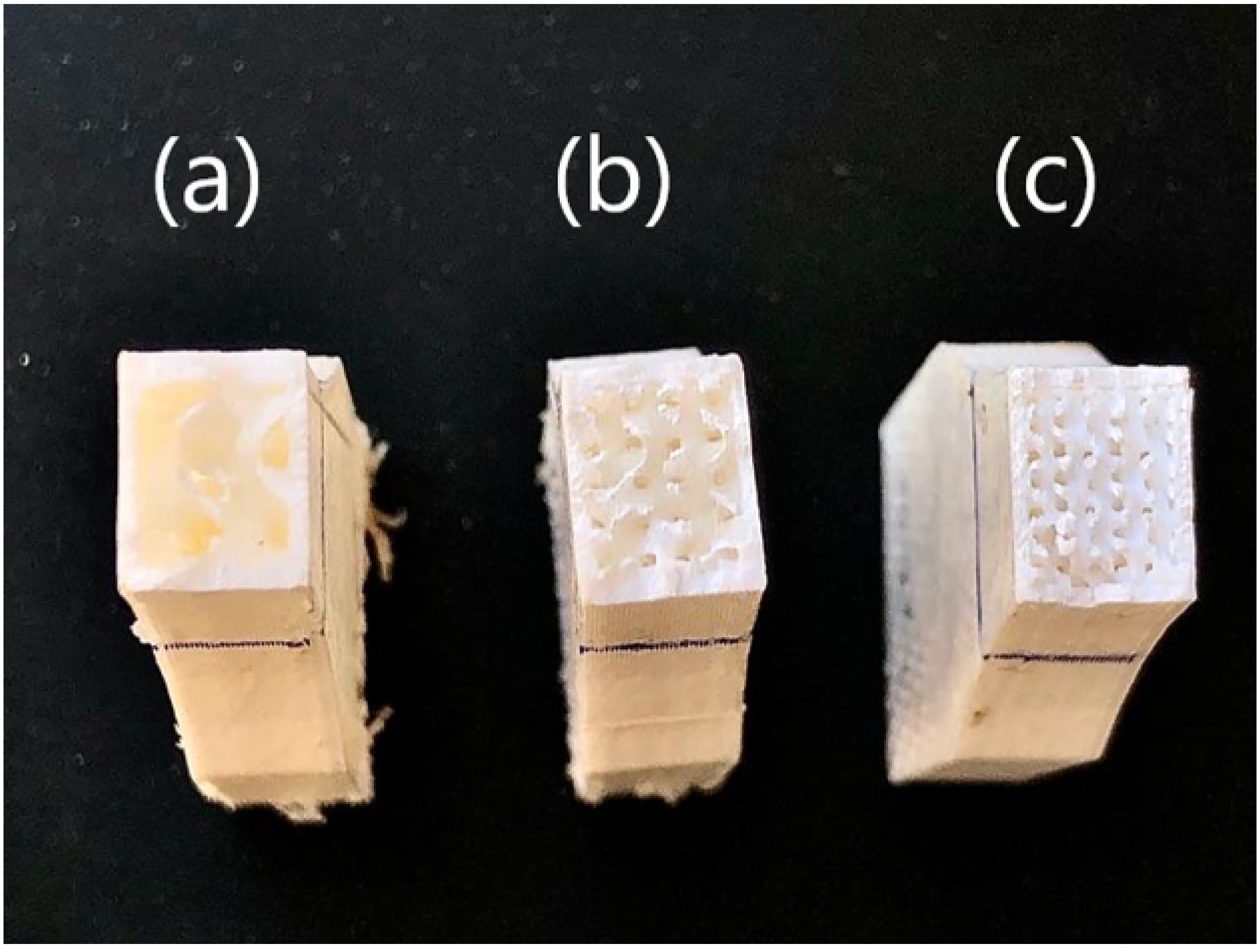

Figure 10

Sections in tested injected ABS specimens with infill: 20% (**a**), 40% (**b**) and 60% (**c**)

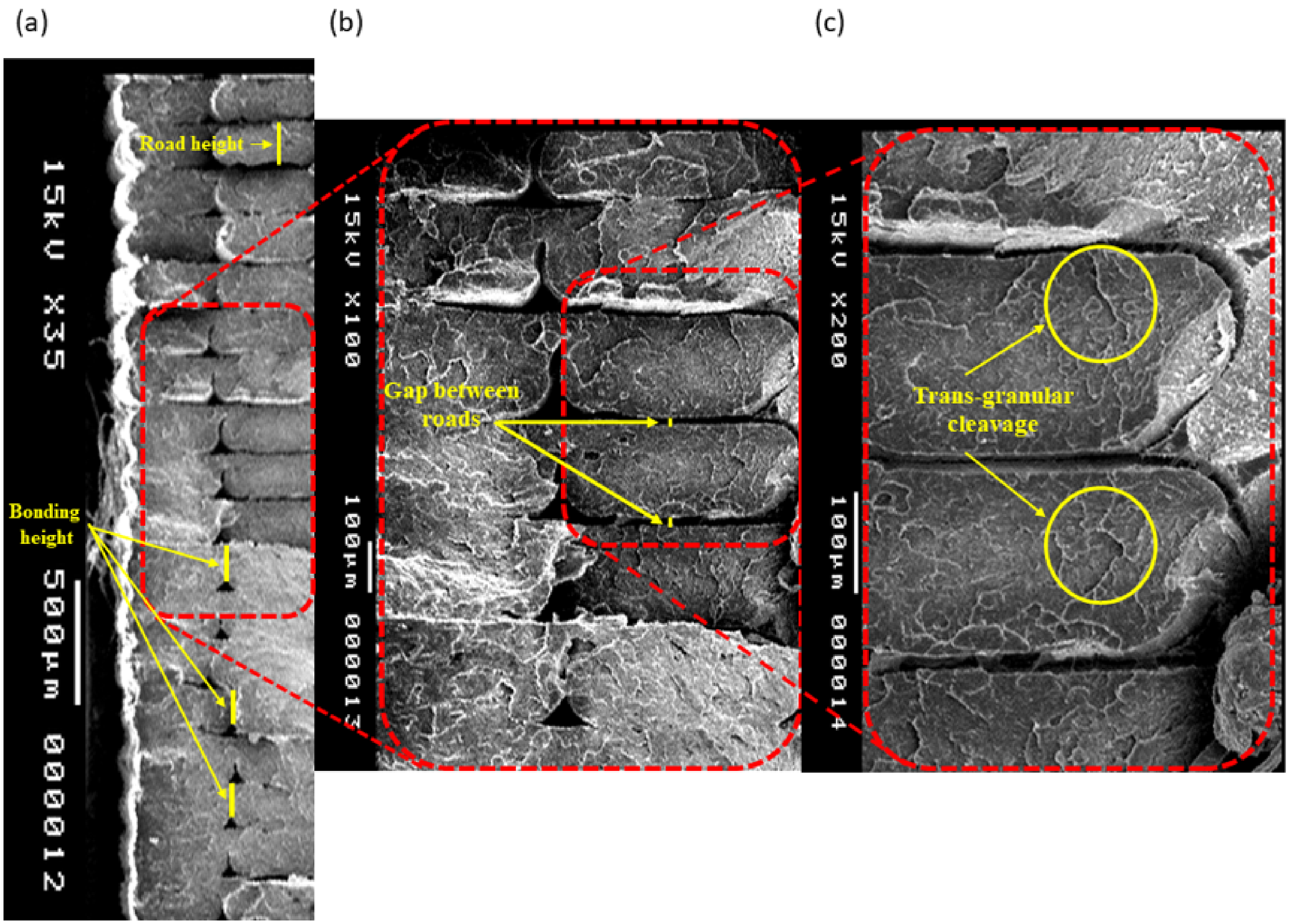

Figure 11

SEM micrograph in ABS specimens: overview for two adjacent roads in different consecutive layers (**a**), bonding in six consecutive layers (**b**), and the circles indicates the trans-granular cleavage in each road (**c**)

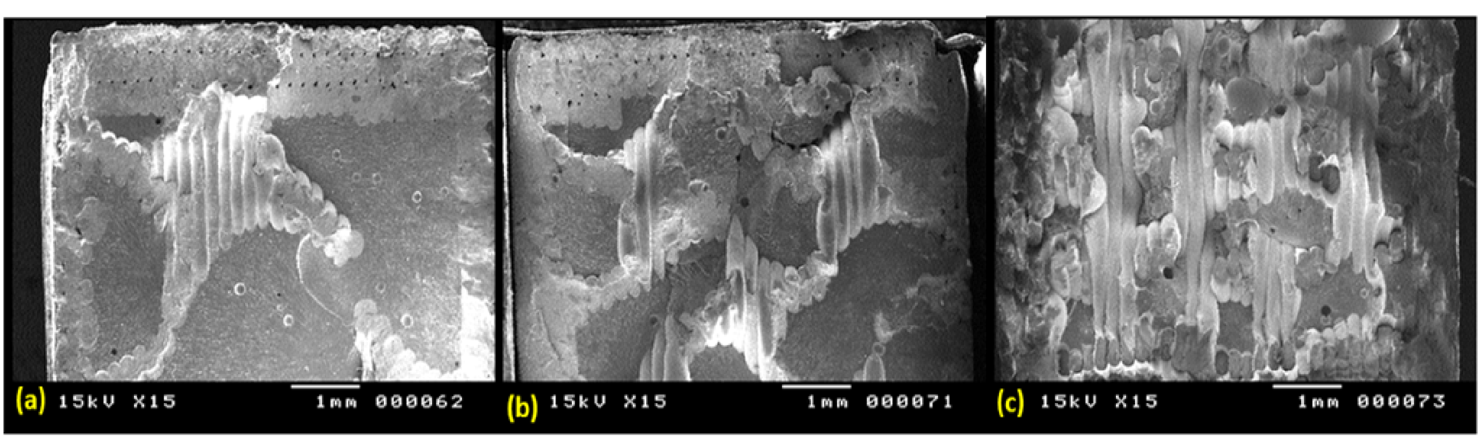

Figure 12

SEM micrographs for: (**20B-80E**) (**a**), (**40B-60E**) (**b**) and (**60B-40E**) specimens (**c**)

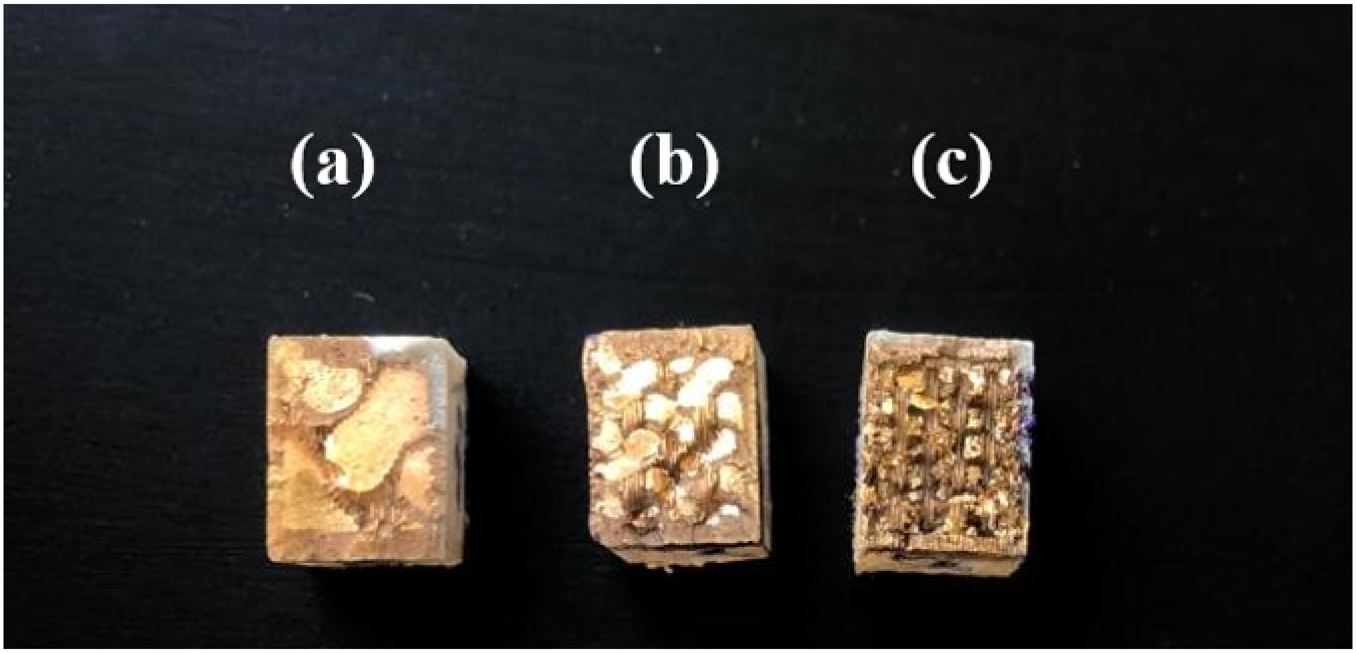

Figure 13

Coated sections in: (**20B-80E**) (**a**), (**40B-60E**) (**b**) and (**60B-40E**) specimens (**c**)

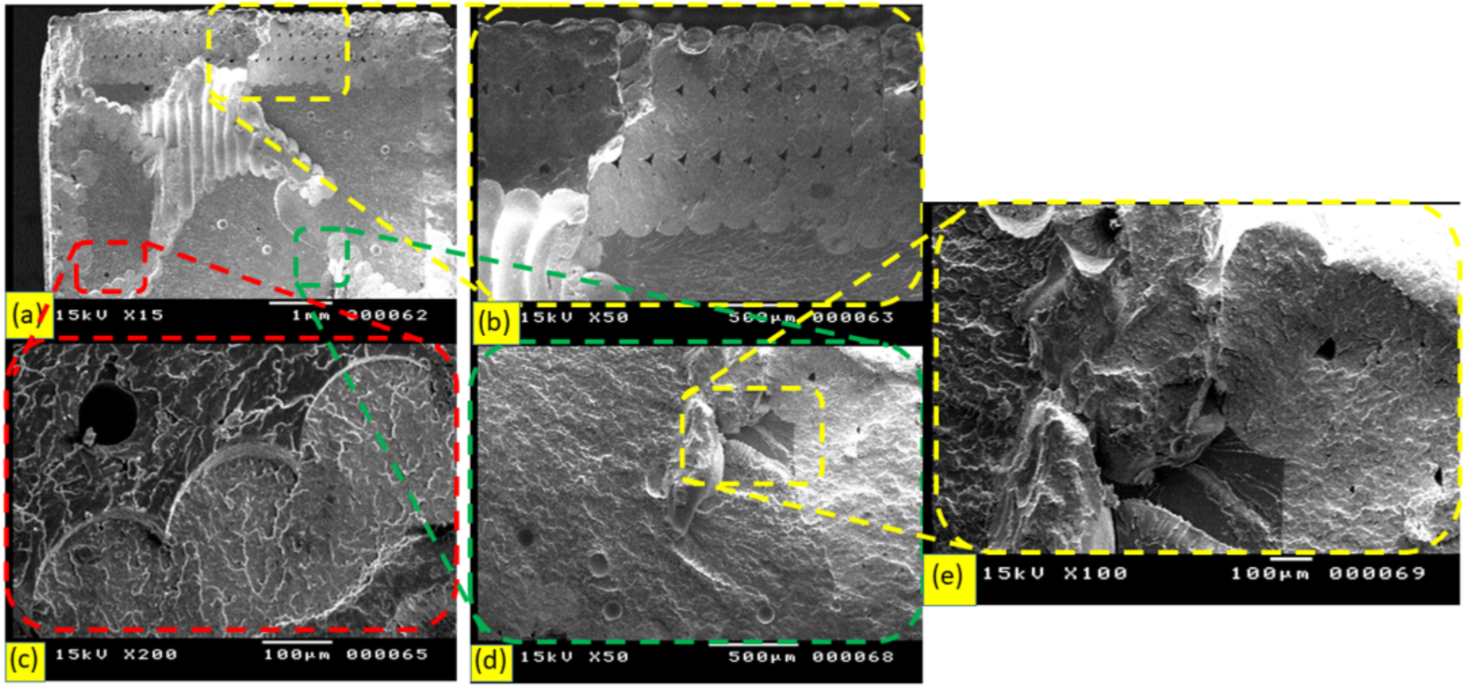

Figure 14

SEM micrographs in (**20B-80E**)

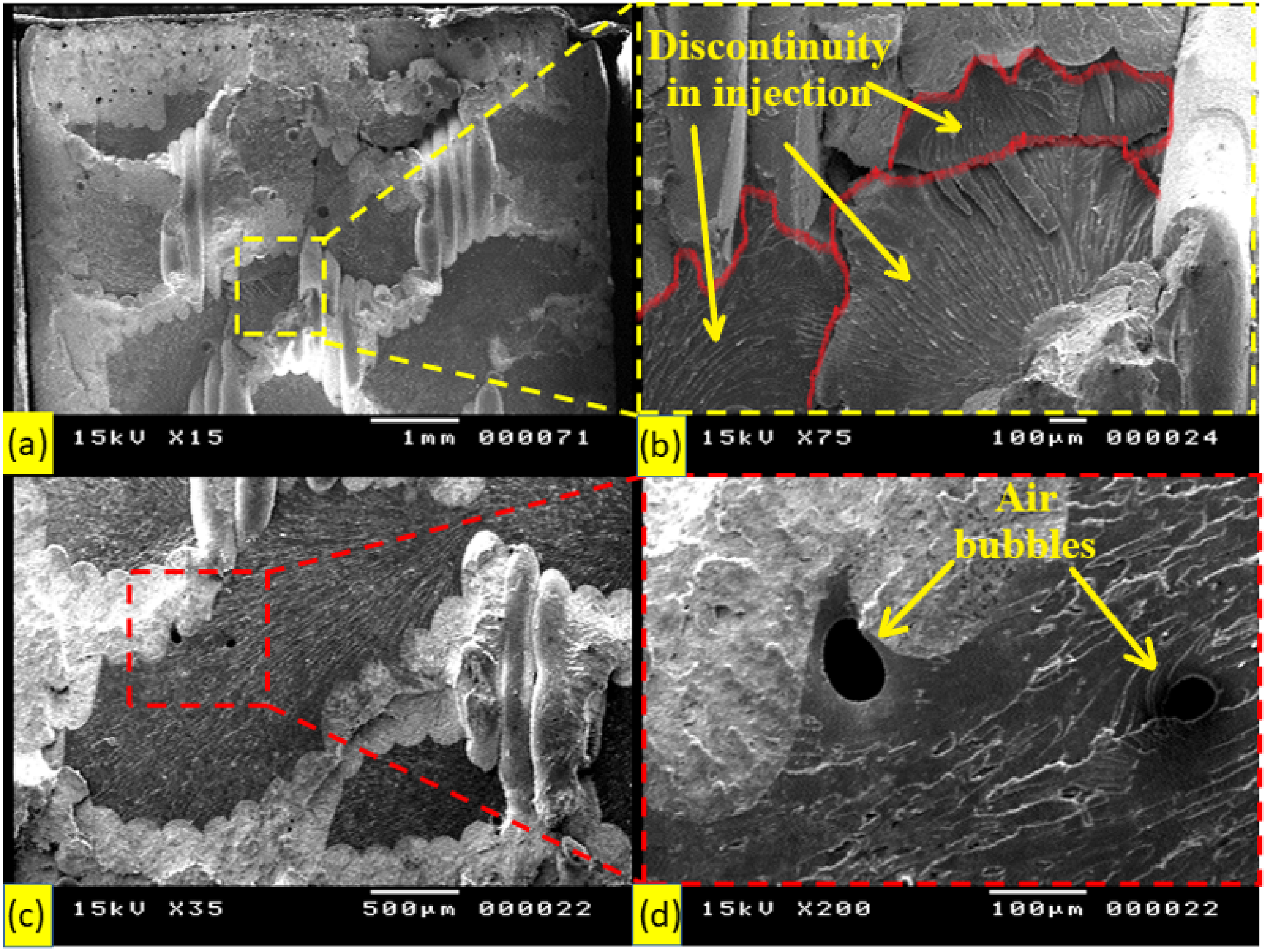

Figure 15

SEM micrographs in (**40B-60E**)

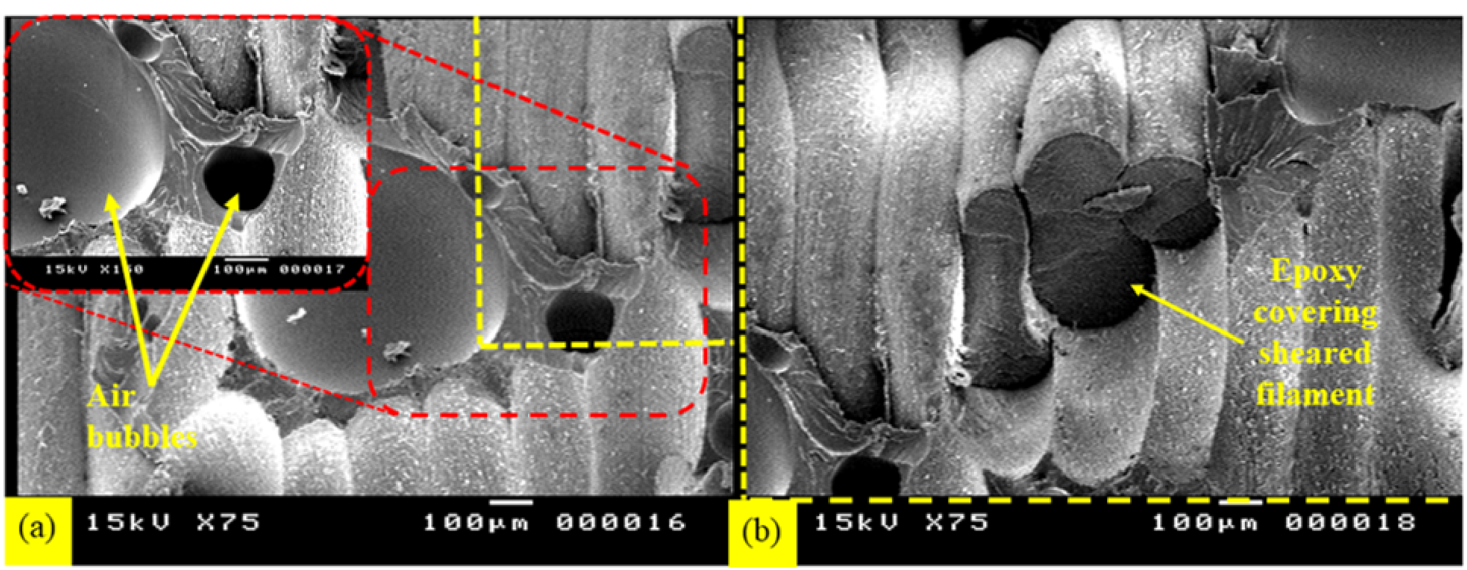

Figure 16

SEM micrographs (**60B-40E**)