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Swarup Ravichandran

R.V. College of Engineering

Vaishnavreddy Bande

R.V. College of Engineering

Siddharth V

R.V. College of Engineering

Raj Aryan Singh

R.V. College of Engineering

Mahantesh M Math

Mahanteshm@rvce.edu.in

R.V. College of Engineering

Bharatish A

R.V. College of Engineering

Sivakumar Solaiachari

R.V. College of Engineering

Prapul Chandra AC

R.V. College of Engineering

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Comprehensive Characterization of SLA-Printed SOMOS Watershed XC 11122 and the Effect of UV Post-Curing on Mechanical, Tribological, Spectroscopic and Morphological Properties

Swarup Ravichandran^a, Vaishnavreddy Bande^a, Siddharth V^a, Raj Aryan Singh^a, Mahantesh M Math^{a*}, Bharatish A^a, Sivakumar Solaiachari^a, Prapul Chandra AC^a,

^a *Department of Mechanical Engineering, R V College of Engineering, Bengaluru, India-560059*

** Corresponding author. Email: Mahanteshm@rvce.edu.in*

Abstract

Stereolithography (SLA) produces high-resolution photopolymer parts whose mechanical and tribological performance depends heavily on post-print Ultraviolet (UV) curing. This study characterises SOMOS Watershed XC 11122, a commercial acrylate resin, printed at 50 μm layer thickness and 450 mW laser power and post-cured at 365 nm and 75°C for 0, 10, and 30 min. Tensile testing (ASTM D638) showed that 10 min curing gave the best results with Ultimate Tensile Strength of 61.1 ± 2.3 MPa and apparent modulus of 1408 ± 75 MPa, which are 17.7% and 35.9% above the uncured group. The 30 min condition fell between the two, confirming a non-monotonic response to cure time. No specimen fractured under three-point bending (ASTM D790), demonstrating good ductility across all conditions. Fourier Transform Infrared (FTIR) and Raman spectroscopy together confirmed near-complete acrylate C=C conversion by 10 min. Between 10 and 30 min, secondary structural changes continued, seen in the vinyl bending mode at 765 cm^{-1} , though the primary conversion peak had already disappeared. Pin-on-disc tribology across five load-speed combinations per cure group revealed that uncured specimens wore dramatically more up to 1943 μm at 20 N compared with cured specimens. At 15 N and 318 RPM, the 30 min specimen achieved the lowest wear depth (32 μm). Scanning Electron Microscopy (SEM) showed directional abrasive grooves on worn surfaces, with groove severity decreasing with cure extent. Energy Dispersive X-Ray Analysis (EDAX) confirmed organic composition (C: 70–74 wt%, O: 21–23 wt%) with minor post-wear oxidation shifts. Surface roughness was 0.30–0.66 μm Ra, and dimensional deviations on uncured cubes ranged from –4.1% to +14.8%. Ten minutes of UV post-curing is recommended for strength-critical applications; 30 min offers better wear resistance at moderate loads.

Keywords: Stereolithography; SOMOS Watershed XC 11122; UV post-curing; Tribology; Coefficient of friction; Wear; SEM; EDAX; FTIR; Raman spectroscopy; Additive manufacturing; Photopolymer; Dimensional accuracy; Surface roughness.

1. Introduction

Additive manufacturing (AM) made designers' ideas come true as lead times shrank and the scope for geometric freedom expanded beyond conventional subtractive machining [1]. Stereolithography belongs to the wider AM field but the resolutions its machines achieve fall below 50 μm resolution, the surface finish exceeds those provided by an extrusion based process whilst the parts' transparency offers an array of optical and fluid uses [2,3]. The SLA printer deposits a beam of focused UV radiation across the liquid bed of resin leaving a polymerised layer where the beam shines through. One pass of the mirror gives a cross-section of the finished part by depositing layer upon layer until an entire component is crafted [4].

All features of the finished part are contingent upon the curing process of the thermosetting resin - both at the time of printing and during further heat / UV curing after removal from the bed [5-8]. The laser only achieves part of the job. Inside the printed specimen, unreacted monomers get trapped in the crosslinked polymer network while the pendant vinyl groups remain unaffected [9]. To reduce residual monomer to negligible amounts, UV curing is then typically used. The UV radiation drives free-radical addition increasing polymerisation thus crosslinks start building up. This increases the elastic modules and hardness of the final product further reducing creep [10,11].

Increasing the degree of cure seems like an all-round advantage however too much radiation has been proven to trigger photo-oxidative chain scission and develop residual shrinkage stresses which undermine the benefits of crosslinking further down the road [12,13]. Non monotonic trend has been witnessed in some acrylate systems before, however little to nothing has been reported looking at a commercial resin used as real-life component.

One formulation used for parts with dimensional accuracy requirements, such as wind-tunnel and casting patterns and microfluidics where its transparency feature provides for new areas of study is, SOMOS Watershed XC 11122 made by Covestro AG commonly referred to as Watershape is an example of an acrylate-epoxy hybrid developed for SLA. It has a low viscosity, with transparency and room temperature stiffness approaching ABS [14]. When a part is fully cured Covestro estimates a strength of 50.4Mpa and a Youngs Modulus over

2.7Gpa. This part of this subject has not been investigated properly to understand the effects of post-cure duration and it is to be understood. The study would encompass mechanical, tribological, morphological and spectroscopic properties.

One way of monitoring what is happening scientifically in a laboratory environment to monitor what resin is being reacted is with the use of the different types of spectroscopy. Through FTIR its possible to identify C=C groups through the stretching of carbon in the alkene found around the value of 1635cm⁻¹. As the curing process becomes more advanced these peaks dissipate. Raman, a similar technology is a method of probing molecular bonds within resin, however without water interference and through transparent material but still at a similar angle compared with FTIR but not necessarily spatially [15-18]. Combining several tools for comparison with the materials data sheet in terms that are understandable. Though, a study has not been conducted on a system to relate data available in materials science to results from an engineering laboratory setting with components to be made using SLA technology using this particular resin.

Tribology testing using SLA resins compared to bulk material is rarely discussed. Where the crosslink density has been previously shown to affect wear in some thermosets through better resistance to plastic deformation near and on parts as well as affecting how parts deform and wear [19-24]. In the case of this photosensitive resin friction, against a metal interface will be affected through the balance of viscous and adhesive mechanisms over cure-duration [25-29]. Tribological study to study friction along with other methods will enable the understanding of when, where and how friction occurs as post-cure duration increases, along with increasing part usability or avoiding situations like jigs and in biomedical instruments that have a tribological application and where friction must be controlled [30-34].

To study surface morphology and deformation, SEM is a practical way of examining tribological conditions as its suitable for studies on a scale that complements confocal profilometry [35]. For use in EDAX and its sister technology the elemental composition including whether there is any elemental shift in layers on the sliding surfaces of transfer films and oxidized layers can be analysed [36-39]. Both to be used before and after testing along with other types of physical tests of the sample. This will help to define wear mechanisms for different components in accordance to how they are used.

All of these threads: tensile and flexural mechanics, FTIR, Raman, multi-parameter pin-on-disc tribometry, SEM, EDAX, confocal roughness, VMM dimensional measurement, are

brought together in this study. The material is SOMOS Watershed XC 11122, it is printed under fixed conditions and then divided across three UV post-cure protocols. The aim is to understand the effects of UV post-curing parameters on various properties of the material.

2. Materials and Methods

2.1. Material and SLA Printing

SOMOS Watershed XC 11122 material, sourced from Covestro AG (formally DSM Somos) was material used. This was an acrylate-epoxy resin, used throughout the experiment for every different kind of specimen. This is optically clear. The resins used for rapid-prototyping in SLA, usually have low viscosity. All specimens originated from the same SLA machine which utilized a UV-laser with 450mW of power with layer steps of 50 μ m, the chamber's temperature remained the same at 21°C throughout. Block-type, self-generating with the software and manually removed after printing, supports with 0.12mm contact diameter were produced through software and subsequently removed by hand once the specimen has finished printing. Each printed part was cleared in isopropyl alcohol beforehand any analysis of its own to discard any surface adhered and un-cured resin.

2.2. Specimen Types and Post-Cure Conditions

Five specimen geometries were manufactured: (i) dogbone tensile bars (ASTM D638 Type I; gauge 13.0 $\times$ 3.0 mm, area 39.0 mm², gauge length 57 mm); (ii) rectangular flexural beams (ASTM D790; 130.0 $\times$ 12.70 $\times$ 3.00 mm); (iii) 10 $\times$ 10 mm cubes for dimensional and tribological use; (iv) cylindrical wear pins derived from the cubes; and (v) flat plate coupons for spectroscopic and morphological analysis. Three post-cure states were defined: Uncured (as-printed, no additional UV), 10 min UV (365 nm, 75 °C), and 30 min UV (365 nm, 75 °C). Specimen set allocations are given in Table 1.

Table 1. Specimen grouping for mechanical testing. Excluded runs are identified in the footnote.

Condition	Tensile Sets	Flexural Sets	n (per test)
Uncured	Set-7, Set-9, Set-10	Set-7, Set-8, Set-9	3
10 min UV	Set-4, Set-5, Set-6	Set-4, Set-5, Set-6	3
30 min UV	Set-1, Set-2, Set-3	Set-1, Set-2	3 tensile / 2 flexural

Note: Tensile Set-8 excluded (anomalous early termination, 760 pts, probable grip slip). Set-4A excluded (mid-displacement supplementary run). Flexural Set-3 / CSIS_1090 excluded (725 pts, incomplete). Flexural CSIS_1078A excluded (peak force ~873 N, an order of magnitude above all other specimens, probable set-up error).

2.3. Mechanical Testing

The test for ASTM D638 was performed on a servo-hydraulic, universal testing machine at ambient condition. Samples were tested in a force-control operation at 2mm/min. With displacement being monitored for 10Hz. A clip-on-extensometer was attached to the gauge sector, readings shown were found to be equal to no-more than 0.16mm at their peak level from the extensor, indicating slip, so crosshead displacement was used exclusively for strain and apparent modulus computation. The three-point bending tests which followed ASTM D790 at a loading speed of 1mm/min for each cure, using a load spanning 48mm. No specimen broke during the procedure, as the sample was bending and did not seem to break, the test was limited by the vertical travel limits of the machine's cross-head.

2.4. Spectroscopic Characterisation

The spectra collected with FTIR for specimens at varying states was within wavenumber 400 to 4000 cm^{-1} in absorbance mode. A test was done in a similar fashion in the Raman spectroscopy of the cylindrical pins of 6mm dia x 5 mm length. This used a spectrometer sourced from Oxford Instruments called WITec alpha 300 R Confocal Raman Microscope with radiation at 532nm. Before the spectrum was taken using the software, we remove cosmic radiation from within. Baseline correction was added and from the analysis, spectra were between 200 and 3200 cm^{-1} .

2.5. Tribological Testing

Tribological wear testing was done with a pin-on-disc machine (Ducom TR-20LE). The rotating wear track disc diameter was 60mm operated at 30 degrees. In each group five samples have been tested which constitute a matrix where a normal load of 10, 15 or 20N is applied on samples that will reach three different speeds (159, 318 or 477RPM in each test). The allocation of samples per testing parameters is described in the table shown on the previous pages, see Table 2. Each experiment lasted for approximately 868 sec, except in 2 cases where wear reached critical level within a fraction of this runtime, being uncured_5 for 529sec and previously uncured_4 for 252sec. From the tribometer-provided data of the frictional force, in

which the COF is just frictional force divided by the load applied on the tested sample by the sliding disc, wear of sample being measured periodically, at almost 1sec and this gives the wear depth. COF values during the remaining 30secs, have been averaged for each parameter to represent the steady-state COF in each conducted test.

Table 2. Tribological test matrix. Each row represents one pin-on-disc run (wear track diameter 60 mm, temperature 30 °C, nominal duration ~868 sec).

Run (Folder/Specimen)	Condition	Load (N)	Speed (RPM)	Duration (sec)	Notes
10min_1	10 min UV	10	318	868	—
10min_2	10 min UV	15	159	868	—
10min_3	10 min UV	15	318	868	—
10min_4	10 min UV	15	477	868	—
10min_5	10 min UV	20	318	868	—
30min_1	30 min UV	10	318	868	—
30min_2	30 min UV	15	159	868	—
30min_3	30 min UV	15	318	868	v2 run; v1 truncated at 252 min
30min_4	30 min UV	15	477	868	—
30min_5	30 min UV	20	318	868	—
uncured_1	Uncured	10	318	868	—
uncured_2	Uncured	15	159	867	—
uncured_3	Uncured	15	318	850	Very high wear; test ran to completion
uncured_4	Uncured	15	477	867	—

uncured_5	Uncured	20	318	529	Truncated; extreme wear
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2.6. Scanning Electron Microscopy and EDAX

We acquired SEM images using a TESCAN VEGA3 LMU SEM. This SEM was used to view the uncured 10 mm cubes before wear and the worn samples. During observation, the acceleration voltage was set to 15.0 kV, the detector was secondary electron mode and the working distances were 15.0 - 17.9 mm. Different magnification was used ranging from 75x up to 3002x, depending on what needed to be seen.

Prior to wear images were obtained at 5 different magnifications for all 3 variations of cure. After wear, SEM images at 5 magnifications each were taken at one specimen per cure condition.

For the acquisition of the EDAX element weight percentages the smart quant algorithm eZAF 25kV, amplifier time constant 7.68 μ s, live acquisition over 30s was used. In total 6 measurements could be carried out: one per cure after wear and one per cure before wear.

2.7. Surface Roughness and Dimensional Accuracy

The surface roughness was measured using an Olympus LEXT OLS4000 confocal laser scanning microscope. This microscope was used at 20x magnification, with an evaluation length of 639 μ m, utilizing a gaussian filter. The cutoff for the uncured and the 10 min cured specimens was chosen as 2500 μ m, while it was 800 μ m for the 30 min cured specimen. This difference in cutoff choice is a limitation which has to be kept in mind when interpreting the roughness measurement data.

An Easson 2D video measuring microscope was employed to record dimensions of each of the uncured cubes. To each surface of the cube, a five-point rectangle was fitted. The resulting dimension was correlated with the nominal value of 10.00 mm.

3. Results and Discussion

3.1. Tensile Properties

Figure 1 shows stress-strain curves for all valid specimens across the three cure groups: uncured, 10 minutes UV and 30 minutes UV. All the curves consist of a distinct linear-elastic part, a gradual knee into non-linear softening before fracture and no discernible yield drop between. Such a pattern is typical of densely crosslinked thermoset networks which fail without exhibiting a significant plastic plateau [33,34].

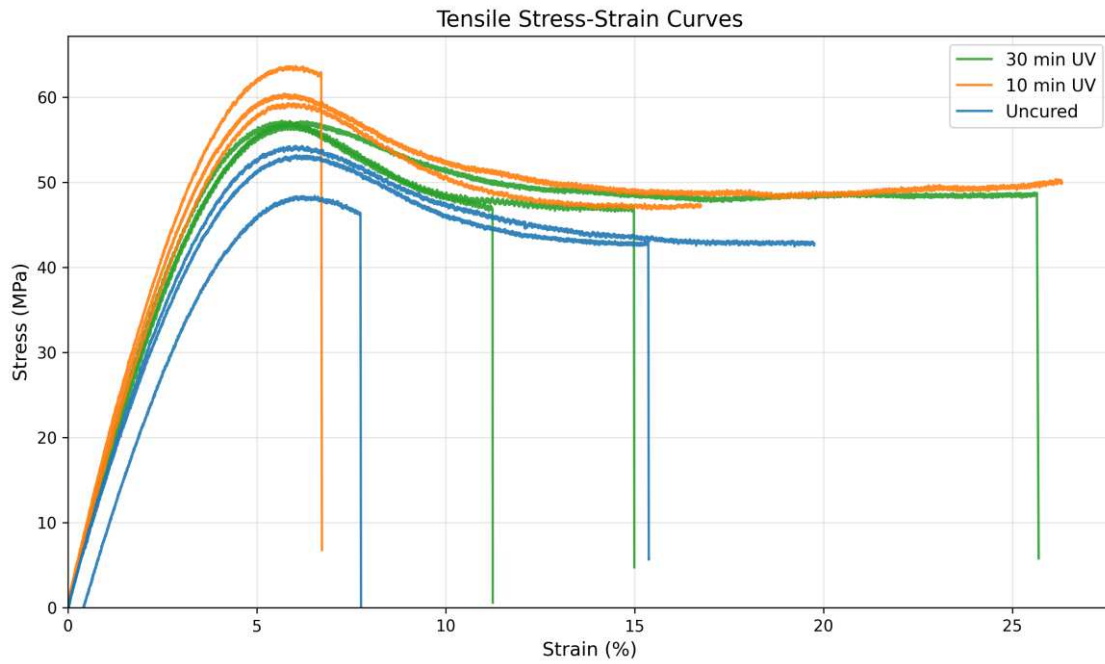


Figure 1. Tensile stress-strain curves for all valid specimens (ASTM D638 Type I). Stress derived from crosshead displacement; gauge area = 39.0 mm², gauge length = 57 mm.

The tabular results for individual and group measurements are presented in Tables 3 and 4. The 10 minutes UV specimens achieved the highest mean UTS among the three cure groups at 61.1 ± 2.3 MPa and the highest apparent modulus at 1408 ± 75 MPa. These were 17.7% and 35.9% higher values than those measured for the uncured group, whose UTS averaged at 51.9 ± 3.1 MPa and modulus at 1036 ± 132 MPa. Positioned between these two extremes, the 30 minutes UV specimens recorded mean values of 57.0 ± 0.3 MPa for UTS and 1274 ± 41 MPa for modulus. The crosshead displacement observed at peak force ranged from 3.3 to 3.5 mm across all test groups. Such a narrow spread is indicative of the non-significant alteration of fracture kinematics by the cure state.

Table 3. Individual specimen peak tensile forces and crosshead displacements at peak.

Condition	Specimen	Peak Force (kN)	Disp. at Peak (mm)
Uncured	Set-7	2.1162	3.436
Uncured	Set-9	1.8871	3.724
Uncured	Set-10	2.0737	3.448
10 min UV	Set-4	2.3553	3.256
10 min UV	Set-5	2.3117	3.328
10 min UV	Set-6	2.4821	3.434
30 min UV	Set-1	2.2295	3.612
30 min UV	Set-2	2.2320	3.231
30 min UV	Set-3	2.2123	3.342

Table 4. Group-level tensile summary. Apparent E derived from crosshead displacement; values underestimate true Young's modulus due to machine compliance (see Section 3.1.1).

Condition	n	UTS (MPa)	SD	App. E (MPa)	SD	Disp. at Peak (mm)
Uncured	3	51.9	3.1	1036	132	3.54 ± 0.16
10 min UV	3	61.1	2.3	1408	75	3.34 ± 0.09
30 min UV	3	57.0	0.3	1274	41	3.40 ± 0.20

3.1.1. Measurement Limitation

The extensometer showed readings of less than 0.16 mm at peak force for every specimen, pointing to jaw slip occurring during the test. For this reason, crosshead displacement was used for all modulus calculations [25,35]. Considering that crosshead displacement incorporates machine-frame compliance as well as grip seating movement, it overstates the actual deformation, leading to modulus values that are lower than the material's true stiffness. While Covestro states an E -modulus of around 2700 MPa for fully cured Watershed XC 11122 [16], our measured apparent moduli varied between 1036 and 1408 MPa. Nevertheless, for the purpose of relative comparison between different cure conditions, the ranking extracted remains meaningful as the same extent of compliance was present for all specimens.

3.1.2. Mechanistic Interpretation

Ten minutes of UV exposure effectively cured most of the residual acrylate C=C bonds. The degree of conversion is further validated in Section 3.3. This results in the formation of a denser network, constraining chain mobility and thereby enhancing load transfer capabilities [36,37]. The 10 min UV group thus emerged as the strongest. The 30 min UV group, while more crosslinked than its uncured counterparts, paradoxically exhibited lower UTS and modulus than the 10-minute group. This effect is most plausibly attributable to photo-oxidative chain scission and thermally induced residual stress, both of which are exacerbated by prolonged irradiation of an already dense polymer network [12,13]. The 30min group produced a tightly grouped set of UTS values (SD = 0.3 MPa), indicating good specimen-to-specimen consistency. In contrast, the uncured group showed a larger variation (SD = 3.1 MPa), which can be attributed to the inherent variability in monomer distribution within as-printed components. To draw statistically significant conclusions concerning these observed differences, ANOVA would be required on a larger dataset. Given that $n=3$ per group, rigorous statistical inferences are not warranted [38].

3.2. Flexural Properties

Figure 2 shows force-deflection curves. None of the specimens were found to be fractured. Instead, they deformed until reaching the endpoint of the universal machine's stroke, which varied between 16 and 36 mm depending on final position of the stroke. This showed excellent proof of ductility and internal energy absorption by the beams made of said resins [26,39].

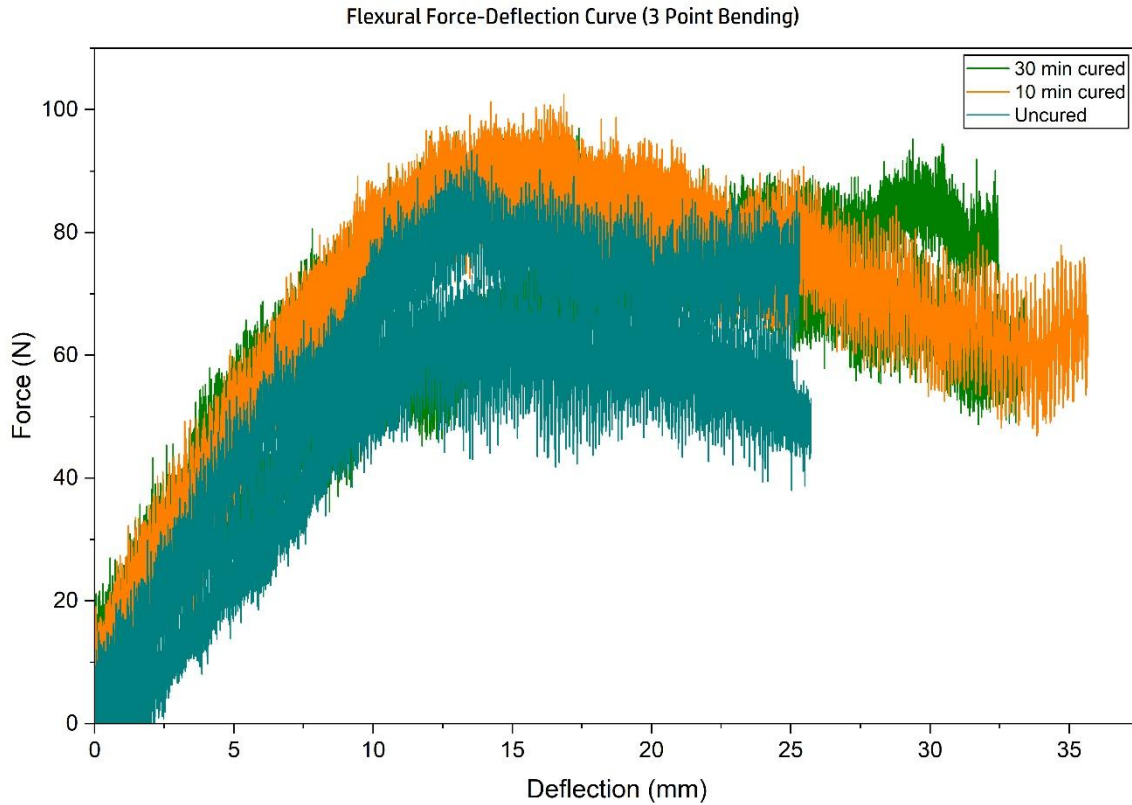


Figure 2. Flexural force-deflection curves (ASTM D790, span = 48 mm).

Table 5 shows the maximum load, bending stress and maximum deflection at the point where the test ended. These results do not show anything broken. Since no specimen was fractured, these results represent the load sustained at the test endpoint rather than the true flexural strength of the material. Max load was sustained by 10 min UV cured specimens which was between 99.2 N and 102.5 N respectively while loads sustained by 30 min cured specimens were between 95.2 N and 97.5N and by uncured specimens were between 77.8 and 93.3N. This is similar to what was observed with tensile strength results. UV curing increases bending stiffness without inducing brittleness according to the experimental data collected, which shows that it is useful in practice [40,65].

Table 5. Flexural results at machine travel limit. Values are not flexural strengths; no fracture occurred.

Condition	n	Max Force (N)	Max Deflection (mm)	Stress at Limit (MPa)
Uncured	3	74.7–93.3	25.1–25.7	47.1–58.7

10 min UV	3	99.2–102.5	25.1–35.7	62.5–64.5
30 min UV	2	95.2–97.5	16.2–34.4	59.9–61.4

3.3. Fourier Transform Infrared Spectroscopy (FTIR)

Figure 3 shows superposition of the full spectra for the three cure states (400 - 4000 cm^{-1}). This is followed by Figures 4-6 showing three characteristic regions.

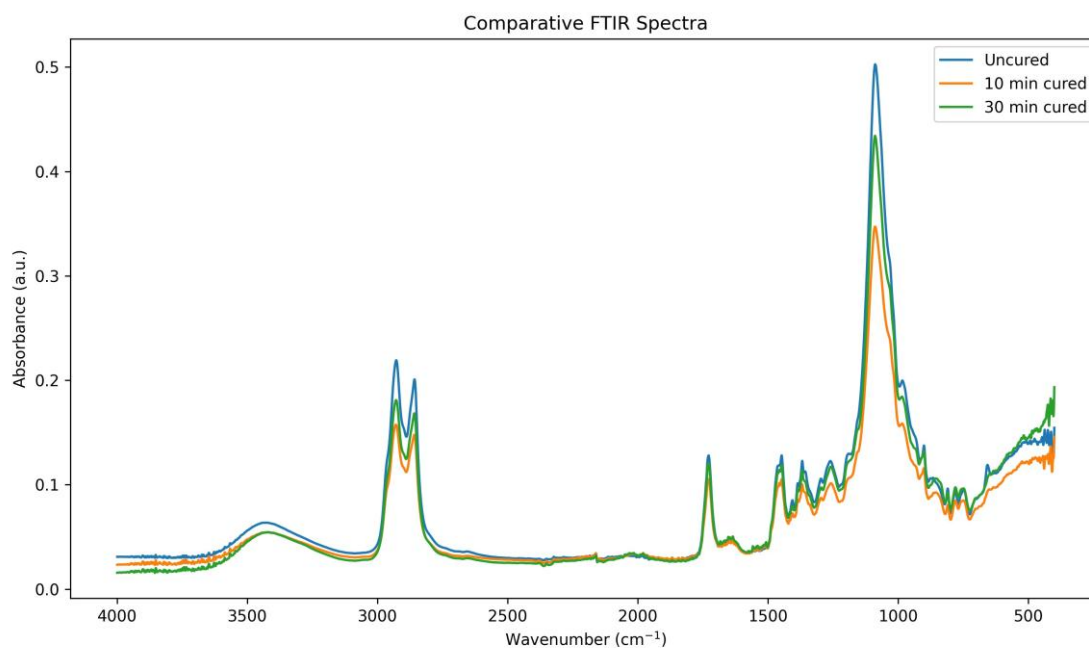


Figure 3. FTIR absorbance spectra of uncured, 10 min cured, and 30 min cured SOMOS Watershed XC 11122 (400–4000 cm^{-1}).

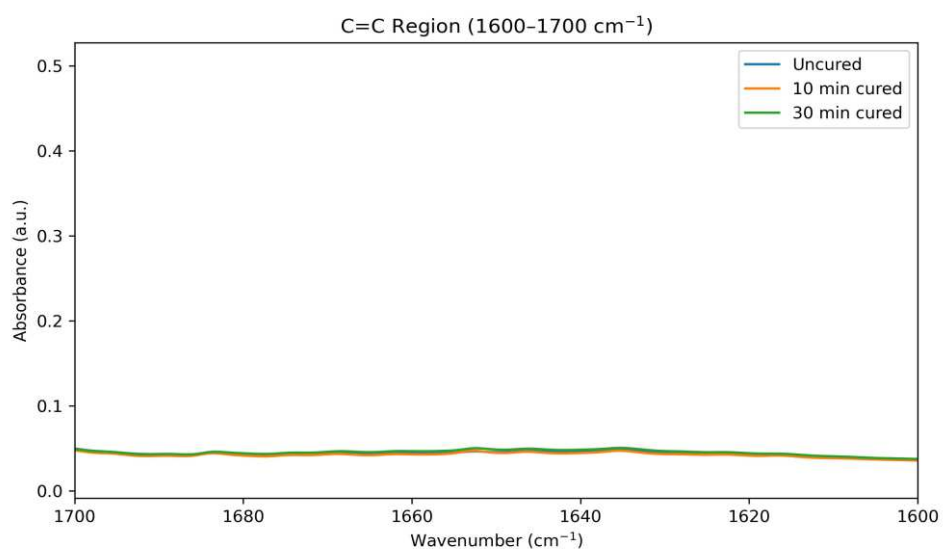


Figure 4. Expanded view of the C=C stretching region (1600–1700 cm^{-1}).

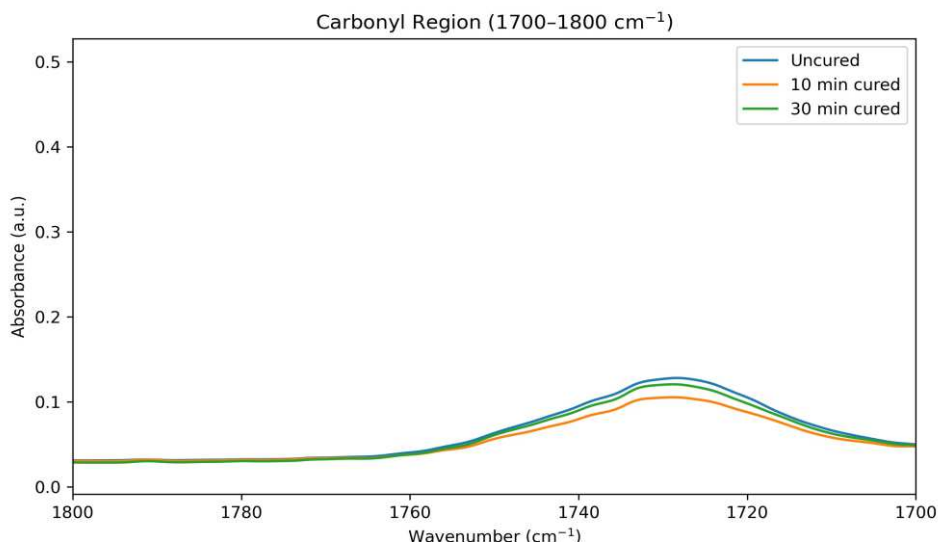


Figure 5. Expanded view of the carbonyl C=O stretching region (1700–1800 cm^{-1}).

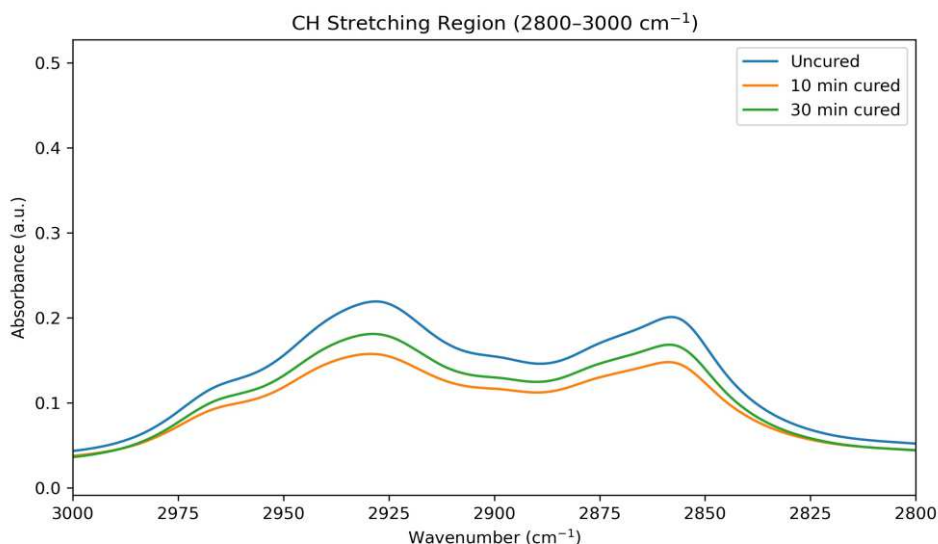


Figure 6. Expanded view of the aliphatic C–H stretching region (2800–3000 cm^{-1}).

Near 1635 cm^{-1} in Figure 4 the absorbance is low and appears relatively flat for all three states. This explains how the laser had already removed most of the vinyl groups during processing. The remaining C=C signal is barely above detection [18,20]. Carbonyl bands around 1728 cm^{-1} showed different trends in Figure 5. The signal had maximum intensities for the uncured specimen, dropped at 10 min, then partially increased at 30 min. It shows how the local environment of carbonyl ester groups changes as crosslinking stiffens the structure. During secondary oxidation a partial recovery could be expected at 30 min as a result of photo-degradation [21,41]. Near to the C-H region in Figure 6, again the uncured specimen showed the highest intensities and the cured specimens had lower values. As crosslinking stiffens the

structure, reduced CH₂ rocking modes and decreased methylene stretching could explain this behaviour [42,43].

3.4. Raman Spectroscopy

Figure 7 shows the Raman spectra from 200 to 3200 cm⁻¹. Assignments for some particular peaks have also been tabulated and their respective counts at various cure times are represented in Table 6.

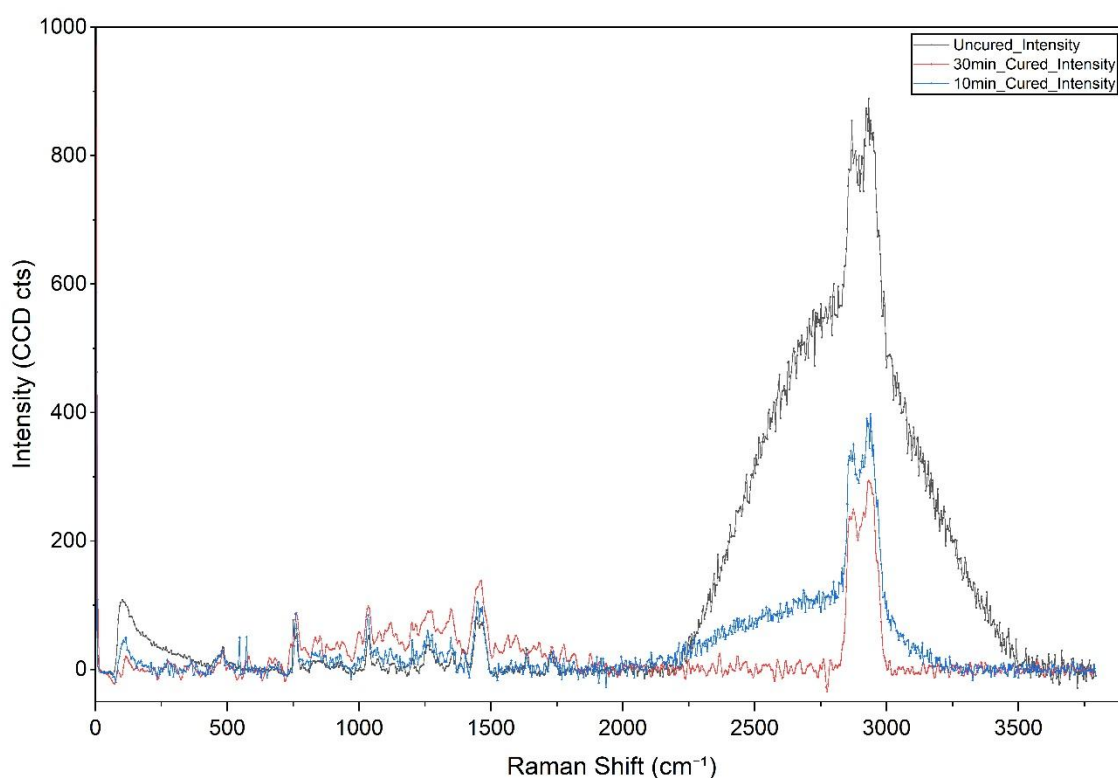


Figure 7. Raman spectra (532 nm excitation) for all three cure conditions over the full spectral window.

Table 6. Raman peak assignments, positions, and integrated intensities (CCD counts) for one specimen per cure condition.

Assignment	Position (cm ⁻¹)	Uncured (cts)	10 min (cts)	30 min (cts)
C=C stretch (acrylate)	~1635	27.6	Not detected	Not detected
C=O stretch (ester)	~1728	27.4	—	—

CH ₂ bending	~1450	98.5	120.0	102.2
C–O–C stretch	~1035	54.3	51.2	53.1
C=C–H bend (vinyl)	~765	99.7	96.2	57.7
CH ₂ sym. stretch	~2871	146.4	158.5	176.2
CH asym. stretch	~2930	52.2	125.8	138.1

The 1635 cm⁻¹ C=C peak present in the uncured state with 27.6 counts is found missing in both of the cured ones which clearly showed with further evidence that monomer conversion using UV post-curing for 10 min brings the reaction closer to completion [19,22,37]. The vinyl C=C-H bending mode at 765 cm⁻¹ showed a decrease from 99.7 to 96.2 and then to 57.7 counts from uncured, 10 min to 30 min cured states respectively suggesting the consumption of pendant groups was still ongoing during 10-30 min interval [20]. CH₂ bending band at 1450 cm⁻¹ showed increased counts from 98.5 to 120.0 following 10 min of curing. The stiff backbone dynamics occurring from increased crosslinking density causes an increase in spectrum for that mode, which upon curing for 30 minutes decreases slightly to 102.2 possibly due to micro-heterogeneity in density occurring as the crosslinking continues [44]. C-H stretching bands at 2871 and 2930 cm⁻¹ are seen to increase steadily and are consistent with the incorporation of CH₂ into the forming resin [44,45]. The Raman results supported the findings obtained through FTIR spectrum. Hence, to some extent it has been proven from all spectroscopic studies that, under the condition used, 10 minutes curing time is sufficient for saturation of the reaction leading to crosslinking.

3.5. Tribological Properties

The wear test programme comprises 16 pin-on-disc runs, five from each of the three cure groups, except that the 30min_3 folder contains both a short preliminary run and a full-duration run; the full-duration run was used throughout. Figure 8 shows the progression of COF over time for each run. Results from different cure conditions are shown separately. Figure 9 plots final wear depth against load for each run, with disc speed indicated by the shape of the graph marker. Figure 10 compares steady-state COF and final wear depth for the matched-condition

runs at a load of 15 N and a speed of 318 RPM. Full results are listed in Table 7.

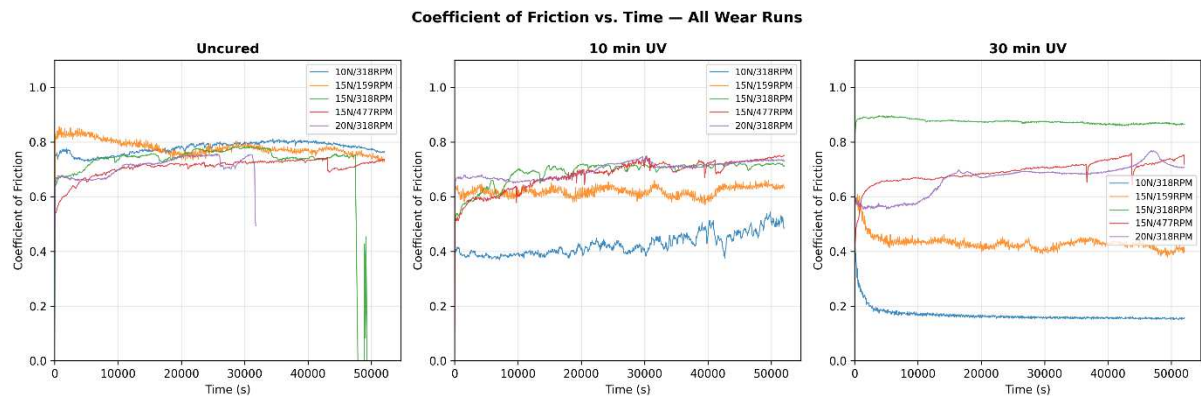


Figure 8. Coefficient of friction versus sliding time for all 15 wear runs, grouped by cure condition.

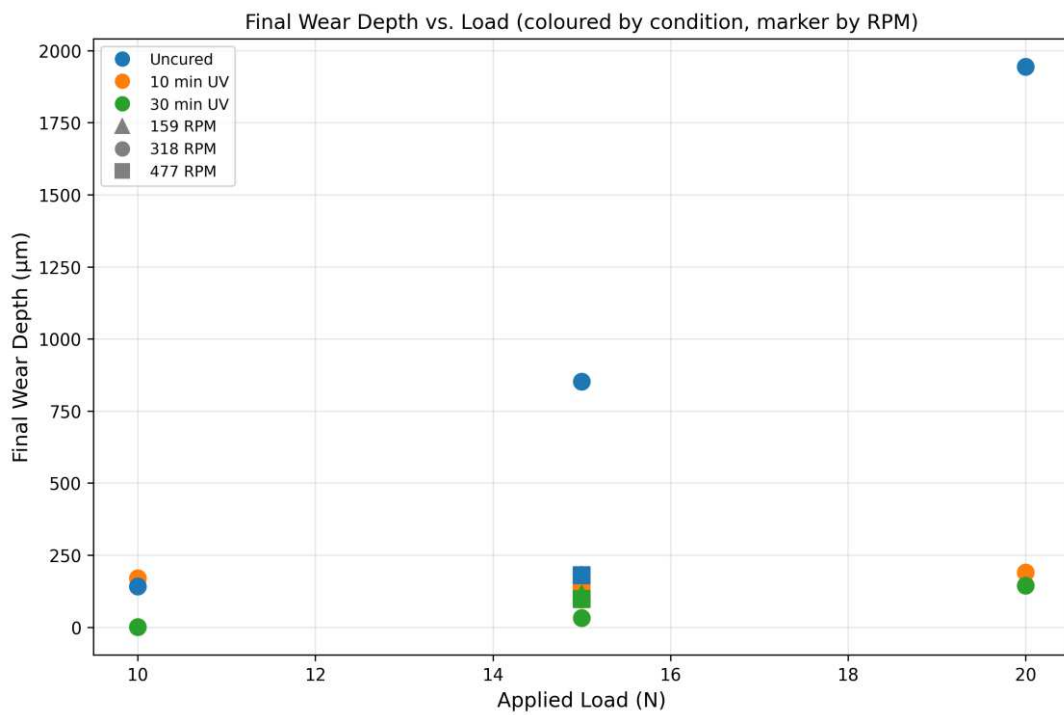


Figure 9. Final wear depth versus applied load for all runs.

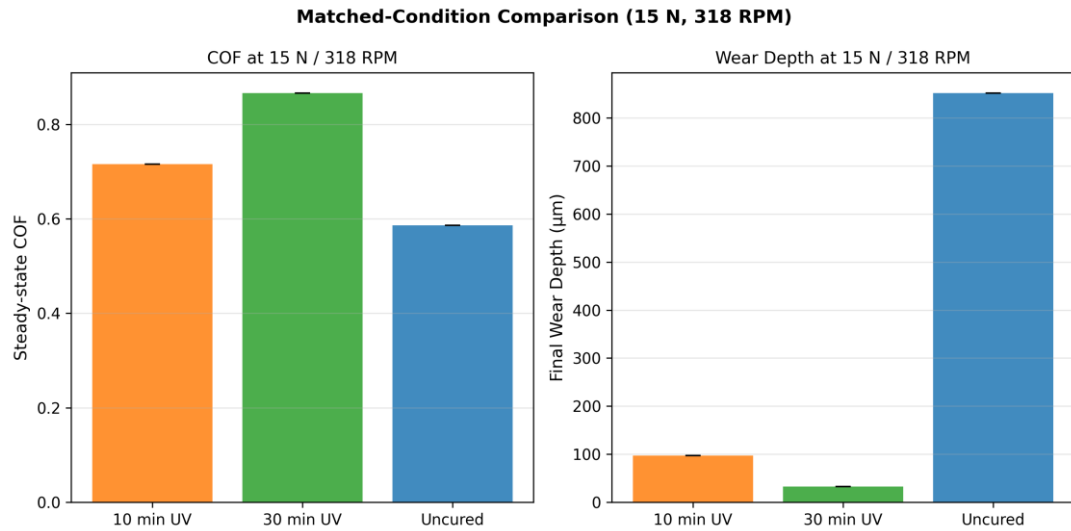


Figure 10. Matched-condition comparison at 15 N and 318 RPM: (a) steady-state COF and (b) final wear depth. Only one run per condition satisfies this exact parameter pair.

Table 7. Tribological results for all 15 wear runs.

Run / Specimen	Condition	Load (N)	RPM	SS COF	Final Wear (μm)
10min_1	10 min UV	10	318	0.472	170.6
10min_2	10 min UV	15	159	0.625	104.2
10min_3	10 min UV	15	318	0.716	96.8
10min_4	10 min UV	15	477	0.726	120.0
10min_5	10 min UV	20	318	0.723	190.2
30min_1	30 min UV	10	318	0.156	1.1
30min_2	30 min UV	15	159	0.421	115.9

30min_3	30 min UV	15	318	0.866	32.4
30min_4	30 min UV	15	477	0.729	98.3
30min_5	30 min UV	20	318	0.713	144.4
uncured_1	Uncured	10	318	0.788	142.4
uncured_2	Uncured	15	159	0.762	183.4
uncured_3	Uncured	15	318	0.586	851.8
uncured_4	Uncured	15	477	0.723	180.7
uncured_5	Uncured	20	318	0.731	1943.8

Note: uncured_5 run was interrupted at 529 sec due to extreme wear. SS COF = steady-state coefficient of friction. 30min_1 result (COF = 0.156, wear = 1.1 μm) is an outlier investigated in Section 3.5.1.

3.5.1. Friction Evolution and Steady-State Behaviour

As per the results visible from Figure 8, it is observed that all three cure periods go through a running-in period during the first 5-10 min of testing. The coefficient of friction appears high at the start of the test and then settles with time. This behaviour is typical in polymer tribological studies because the surface asperities wear down and a transfer film gradually builds up on the rotating metal disc as wear progresses [50,53].

The COF range is the maximum for the uncured samples in the dataset where values ranging from as low as 0.586 till as high as 0.788 were observed. Less-crosslinked chain structure in uncured thermosets means that they are more likely to undergo viscous flow as well as material transfer, which leads to formation of an inhomogeneous tribofilm on the counterface thereby making the COF hard to predict [50,51]. For the samples from 10 minute cure group, values ranging from as low as 0.472 and as high as 0.726 were observed. Higher loads slightly reduced COF through increased contact area and thermal softening, while higher speeds increased friction through hydrodynamic dissipation effects [53,55].

However, for the 30min cure group, one reading at 10N and 318rpm showed extraordinarily low wear depth and a low value of COF at just 0.156. The corresponding wear depth was only 1.1 μm which was substantially lower than that observed in the other runs. This behaviour does

not follow the trends observed elsewhere in the dataset. The result may be attributed to the formation of a soft lubricating transfer film or a quasi-lubricated contact that was caused by particulate debris from the steel disc. Other contributing factors may include specimen surface preparation or local resin heterogeneity [54,57]. Nevertheless, no conclusions were drawn regarding the effect of extended curing on the tribological behaviour of this group based on this isolated result.

3.5.2. Wear Depth and Load-Speed Dependence

The tribological finding that is most pronounced in Figure 9 is the fact that the uncured specimens show higher wear compared to both cured states at the same load and speed. At 15 N and 318 RPM, in case of uncured specimen (uncured_3) 851.8 μm wear accumulated whereas for 10 min specimen 96.8 μm wear was found and only 32.4 μm wear accumulated for 30 min specimen at the same load and speeds. At 20 N and 318 RPM, uncured_5 reached 1943.8 μm wear before the test was stopped at 529 seconds. This provides convincing results for explaining wear resistance in terms of crosslink density. When molecules are just cross-linked loosely due to the uncured state they can deform viscoelastically at site of contact. This results in chain pull-out forming most of its wear [48,52].

Within the cured groups, wear depth increases with load in the expected manner for abrasive-dominated polymer wear regimes [54,59]. The 10 min group at 20 N (uncured_5 analogue: 10min_5) reached 190.2 μm , approximately double the 15 N result (96.8 μm), consistent with a near-linear pressure dependence of polymer wear [53]. The 30 min group shows lower absolute wear at 15 N (32–98 μm) than the 10 min group, despite nominally similar tensile strength, suggesting that extended curing may introduce a small quantity of lubricating low-molecular-weight oligomers that reduce adhesive component of wear, or that the denser network simply has lower capacity for visco-plastic deformation [52,56]. The anomalous 30min_1 point (1.1 μm) is excluded from this trend discussion.

3.6. Scanning Electron Microscopy (SEM) Morphology

Figure 11 compares representative before-wear (without-wear) SEM images at low magnification (250 $\times$) for the three cure conditions. Figure 12 shows the corresponding worn surfaces (run_3 specimens, 75 $\times$ overview and 200–500 $\times$ detail).

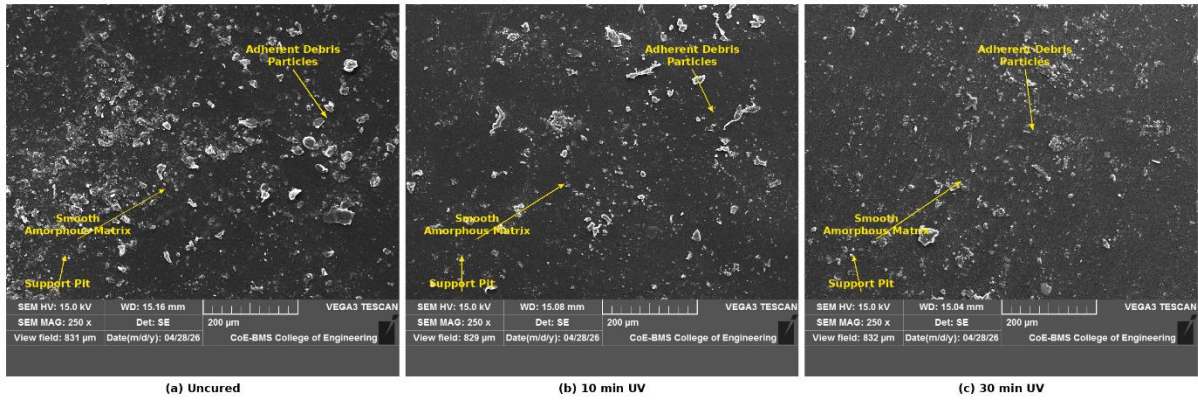


Figure 11. SEM micrographs of as-printed pin surfaces before tribological testing (TESCAN VEGA3 LMU, 15 kV, SE mode, 250 $\times$, scale bar 200 μ m). Left: Uncured; Centre: 10 min UV; Right: 30 min UV.

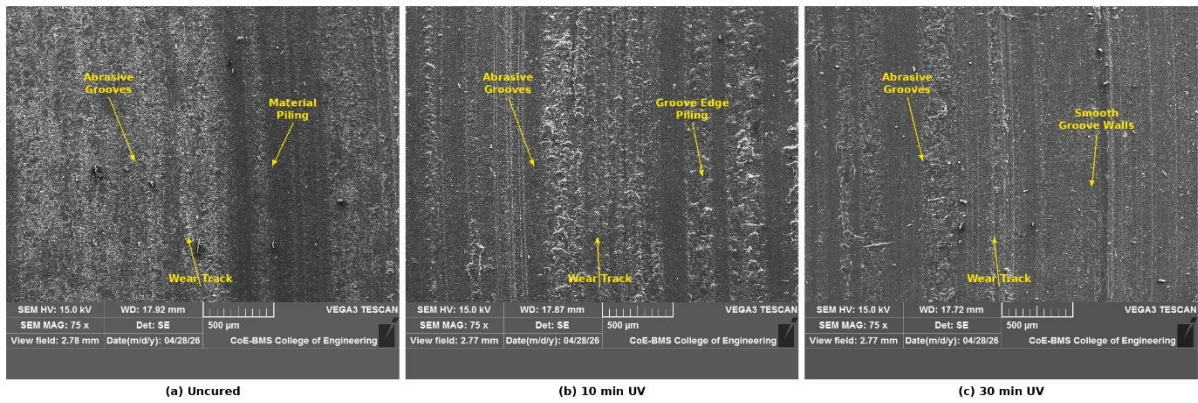


Figure 12. SEM micrographs of worn pin surfaces after tribological testing (75 $\times$, scale bar 500 μ m). Left: Uncured (uncured_3, 15 N / 318 RPM); Centre: 10 min UV (10min_3, 15 N / 318 RPM); Right: 30 min UV (30min_3, 15 N / 318 RPM).

Pre-wear the three cure conditions look much the same at 250 $\times$. Each has a smooth amorphous matrix with discrete bright chunks sitting atop of it, roughly 10-50 μ m big. Occasional shallow pits are spots where supports gripped and where layers lie respectively. The chunk density is much the same over the cure conditions as evidence of whether surface was untouched in between at this scale after curing [60,61].

Post-wear surfaces (Figure 12) tell a markedly different story. All three worn specimens display longitudinal abrasive grooves oriented along the sliding direction, consistent with two-body abrasion by counterface asperities ploughing through the polymer [54,58]. On the uncured specimen (Figure 12), the grooves are wide, deeply shadowed, and accompanied by extensive material piling at groove edges, reflecting the large plastic strains and adhesive transfer enabled by the loosely crosslinked network [50,52]. The 10 min cured surface (Figure 12) exhibits

narrower grooves with less edge piling, and the groove-to-groove spacing is more regular, indicating more uniform material removal from a stiffer substrate. The 30 min cured surface (Figure 12) shows similarly discrete grooves but with higher groove-wall smoothness, potentially attributable to the slightly higher crosslink density restricting sub-surface plastic flow [48,59].

3.7. EDAX Elemental Composition

Result tables of all six eZAF Smart Quant analyses were collected in Table 8. All specimens were predominately carbon-based as would be expected for an acrylate photopolymer. C (70-74 wt%), O (21-23 wt%) and N (1.5-3.9 wt%) were the main elements. Chlorine was between 2.2 and 2.7 wt%. Some specimens also showed traces of P, S and Si.

Table 8. EDAX elemental composition (wt%) from eZAF Smart Quant quantification (25 kV, 30 s live time, one area per specimen).

Specimen	C (wt%)	N (wt%)	O (wt%)	Cl (wt%)	S (wt%)	P (wt%)	Other
Before wear — 30 min UV	73.59	2.77	20.91	2.51	0.22	—	—
Before wear — Uncured	72.41	3.91	20.86	2.34	0.14	0.10	Si 0.24
Before wear — 10 min UV	73.26	2.72	21.57	2.23	0.12	0.10	—
After wear — 10 min UV	70.63	3.65	22.71	2.74	0.15	0.13	—
After wear — 30 min UV	72.59	1.50	22.99	2.64	0.27	—	—
After wear — Uncured	72.85	1.78	22.42	2.69	0.27	—	—

The elemental composition is consistent with the known chemistry of acrylate photopolymers: the high carbon content reflects the polymer backbone and aromatic/aliphatic side chains; oxygen derives from ester and ether linkages; nitrogen suggests urethane or amine- containing photoinitiator residues; and chlorine has been reported as a trace contaminant or resin additive

in several commercial photopolymer formulations [62,63]. The Si detected in the uncured before-wear specimen may reflect residual mould-release agent or airborne silicone contamination; it is absent from all other measurements. Comparing before-wear to after-wear compositions within each cure condition reveals a consistent pattern: oxygen content increases post-wear (by 1.1–0.6 wt% for 10 min and 30 min, respectively) while carbon content decreases marginally. This shift is mechanistically plausible—sliding contact promotes localised frictional heating that accelerates surface oxidation, and transfer of metal oxide particles from the steel counterface disc could elevate oxygen signal [62,63]. The nitrogen content falls post-wear in both cured conditions, possibly reflecting preferential removal of nitrogen-rich near-surface photoinitiator aggregates during abrasion [63]. The chlorine content increases marginally post-wear across all conditions, which is difficult to rationalise chemically and may reflect measurement area-to-area variability at low weight fractions. All EDAX values carry typical eZAF uncertainties of ± 0.5 – 1.5 wt% for elements above 1 wt% at 25 kV; trace elements should be interpreted with appropriate caution [62].

3.8. Surface Roughness

Result for line roughness parameters obtained from confocal microscopy is shown in Table 9. Ra values for all three cases were below 1 μm , with a range of 0.30 - 0.66 μm depending on the conditions. This is typical for SLA formed at 50 μm resolution [30,31].

Table 9. Confocal line roughness parameters (LEXT OLS4000, 20 $\times$ objective, Gaussian filter, evaluation length 639 μm).

Condition	Ra (μm)	Rq (μm)	Rz (μm)	Rp (μm)	Rv (μm)
Uncured	0.451	0.854	10.395	9.228	1.167
10 min UV	0.663	0.831	4.977	2.861	2.116
30 min UV	0.304	0.476	7.149	5.831	1.319

Note: $\lambda_c = 2500$ μm for uncured and 10 min specimens; $\lambda_c = 800$ μm for 30 min specimen.

Highest was the uncured Rz value with 10.395 μm which can be dominated by one single peak at Rp=9.228 μm which is more likely to be a particle or a surface feature missed when cleaning. The 10 min cured Ra of 0.663 μm is actually higher than uncured 0.451 μm but as n=1 for the measurement and even though it is carried in the same manner, indicates that this result would have come due to either a UV-chamber inducted surface change, a difference for measuring depending on place or it being an actual surface change not purely associated to cure conditions.

Lowest Ra was recorded for 30 min specimen at 0.304 μm but in terms of cut-offs Gaussian cut-off of 800 μm was used here due to change of the method compared to 2500 μm for the other values. This will give Ra reduction results associated to the short-wave component of the surface which is not what needs to be recorded or the real situation of the surface. Ra in this situation is not reliably compared if the cut-offs are not of consistent values for all three specimens [45].

3.9. Dimensional Accuracy

The Vision Measurement Machine (VMM) data consists of thirteen distinctive samples (13 uncured cubes) where Cube 6 was a duplicate and was discarded, Cube 13 gives a width of 8.712mm - so far below the others as to imply angular skew as opposed to any kind of real dimension. See Table 10.

Table 10. *VMM-measured face dimensions of uncured 10 × 10 mm cube specimens (nominal 10.00 × 10.00 mm, Easson 2D microscope).*

Cube	Length (mm)	Width (mm)	Proportion (%)	ΔL (%)	ΔW (%)
1	11.316	10.380	117.5	+13.2	+3.8
2	11.476	10.246	117.6	+14.8	+2.5
3	10.478	9.903	103.8	+4.8	−1.0
4	10.948	9.877	108.1	+9.5	−1.2
5	10.747	10.010	107.6	+7.5	+0.1
7	10.443	9.952	103.9	+4.4	−0.5
8	9.902	9.885	97.9	−1.0	−1.2
9	9.847	9.699	95.5	−1.5	−3.0
10	9.933	9.669	96.0	−0.7	−3.3
11	9.717	9.686	94.1	−2.8	−3.1
12	9.831	9.820	96.5	−1.7	−1.8
13	9.811	8.712	85.5	−1.9	−12.9
14	9.717	9.591	93.2	−2.8	−4.1

Excluding the flagged Cube 13, length deviations range from -2.8% to $+14.8\%$ and width deviations from -4.1% to $+3.8\%$. The upper quartile cubes (1, 2, 3, 4, 5, 7) show positive length deviations attributable to anisotropic cure-induced expansion in the scan plane, consistent with reported SLA over-cure phenomena in the XY plane [27,46]. The lower-quartile cubes (8–14) exhibit small negative deviations in both dimensions, reflecting volumetric contraction upon monomer–polymer conversion [27,28]. The proportion values ($85.5\text{--}117.6\%$) underscore shape distortion beyond simple isotropic shrinkage, which the VMM rectangle-fitting algorithm captures but cannot attribute to a single cause without cross-correlation with build-platform position data [29,47].

4. Conclusions

A systematic, multi-technique characterisation of SLA-printed SOMOS Watershed XC 11122 photopolymer resin under three UV post-cure states (uncured, 10 min, 30 min at 365 nm and $75\text{ }^{\circ}\text{C}$) was carried out and yields the following principal conclusions:

- (1) Tensile strength and apparent modulus both peaked at 10 min of UV curing, at 61.1 ± 2.3 MPa and 1408 ± 75 MPa. Those values are 17.7% and 35.9% above the uncured group. The 30 min condition sat in between. The non-monotonic pattern reflects crosslinking and photo-oxidative chain scission competing as cure time grows.
- (2) No specimen fractured during three-point bending regardless of cure state. Flexural strength could not be determined because no specimen fractured before reaching the machine travel limit. 10 min group qualitatively held the highest force before failure.
- (3) Raman spectroscopy offered clearest distinction between different cure states. The C=C peak of methacrylate (monomer) at 1635 cm^{-1} is present in uncured specimens and absent in samples cured within all tested conditions. FTIR, due to overlap of similar chemical bonds, delivered limited contribution apart from the regions where peaks related to carbonyls and alkyl chains can be found (changes are visible as shift and height variations).
- (4) Tribological testing demonstrated an improvement in wear resistance with increasing curing time. The uncured specimens exhibited significantly higher material removal than the cured groups under all test conditions. At 15 N load and a speed of 318 RPM, the wear depth decreased from $851.8\text{ }\mu\text{m}$ for the uncured specimens to $96.8\text{ }\mu\text{m}$ after 10 min of curing and further to $32.4\text{ }\mu\text{m}$ after 30 min of curing. The 30 min cured specimens showed the lowest wear depth despite exhibiting a relatively high coefficient of friction ($\text{COF} = 0.87$). This observation suggests that the enhanced wear resistance is primarily governed by the increased crosslink

density achieved through curing, indicating that crosslinking has a greater influence on wear performance than the friction coefficient in the investigated resin system.

(5) SEM reveals that pre-wear surfaces carry adherent particulate debris and shallow pits from the SLA process and post-wear surfaces exhibit directional abrasive grooves, with groove width and depth positively correlated with the uncured state, consistent with two-body abrasive wear of a polymer against a harder surface.

(6) The surface composition data received using Energy Dispersive X-Ray confirm mostly organic material of all samples with around 70 to 74 wt% of carbon and 21 to 23 wt% of Oxygen. Presence of Nitrogen may relate to photoinitiator used in the resin. As photoinitiator is consumed, nitrogen concentration on surfaces reduces.

(7) Confocal roughness ($R_a = 0.30\text{--}0.66\ \mu\text{m}$) falls within typical SLA surface quality ranges. Differences between conditions are within the range attributable to measurement-protocol inconsistencies, particularly the differing Gaussian cutoff wavelengths applied.

(8) Using Vision Measurement Machine (VMM) measurements on cubic specimens, which should be $10\times10\times10\text{mm}$ in volume, the effect proportional curing and post curing can be observed on uncured specimen which are expanded $+14.8\%/+14.7\%$ on xy plane versus shrink at 4.1% on z-axes. For samples cured during the manufacturing process, expansion on the plane XY was observed and related to photo polymerisation process which takes place with volume contraction - therefore samples must expand within the xy plane during polymerisation to keep the fixed height.

Where tensile strength needs to be maximised, 10 minutes (365 nm, 75°C) would be a more favourable duration for post curing samples. Wear resistance will benefit more from prolonged exposure, as higher crosslink density directly leads to an order of magnitude increase in durability. In the future studies, samples of sufficient size should be tested to obtain statistically sound results without resorting to extensive modelling. Also proper extensometry should be used to provide values for Young modulus than calculations at single point of failure which results in oversized value for this specific experimental work.

Statements of Declarations

Competing Interest

I declare that the authors have no competing interests as defined by Nature Research, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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Author contributions

Conceptualization: Mahantesh M Math

Methodology: Sivakumar Solaiachari

Investigation & Sample Preparation: Swarup Ravichandran, Siddharth V

Testing & Data Acquisition: Vaishnavreddy Bande, Swarup Ravichandran

Mechanical & Tribological: Siddharth V, Swarup Ravichandran

Spectroscopic & Morphological: Swarup Ravichandran, Vaishnavreddy Bande

Formal Analysis & Data Curation: Prapul Chandra AC, Mahantesh M Math

Writing – Original Draft: Mahantesh M Math

Writing – Review & Editing: Sivakumar Solaiachari

Supervision & Resources: Mahantesh M Math

References

1. Melchels FPW, Feijen J, Grijpma DW. A review on stereolithography and its applications in biomedical engineering. *Biomaterials*. 2010;31(24):6121–6130.
2. Manapat JZ, Chen Q, Ye P, Advincula RC. 3D printing of polymer nanocomposites via stereolithography. *Macromolecular Materials and Engineering*. 2017;302(9):1600553.
3. Jacobs PF. *Rapid Prototyping & Manufacturing: Fundamentals of Stereolithography*. Dearborn (MI): Society of Manufacturing Engineers; 1992.
4. Chockalingam K, Jawahar N, Chandrasekhar U. Influence of layer thickness on mechanical properties in stereolithography. *Rapid Prototyping Journal*. 2006;12(2):106–112.
5. Hague R, Mansour S, Saleh N. Material and design considerations for rapid manufacturing. *International Journal of Production Research*. 2004;42(22):4691–4708.
6. Stansbury JW, Idacavage MJ. 3D printing with polymers: challenges among expanding options and opportunities. *Dental Materials*. 2016;32(1):54–64.
7. Chockalingam K, Jawahar N, Chandrasekhar U. Influence of UV post-curing on mechanical properties of stereolithography parts. *Journal of Coatings Technology and Research*. 2019;16:1525–1534.
8. Salmoria GV, Ahrens CH, Beal VE, Pires ATN, Soldi V. Evaluation of post-curing and laser manufacturing parameters on the properties of SOMOS 7110 photosensitive resin used in stereolithography. *Materials & Design*. 2009;30(3):758–764.
9. Crivello JV, Reichmanis E. Photopolymer materials and processes for advanced technologies. *Chemistry of Materials*. 2014;26(1):533–548.
10. Kotz F, Arnold K, Bauer W, Schild D, Rath N, Rapp BE. Three-dimensional printing of transparent fused silica glass. *Nature*. 2017;544:337–339.
11. Decker C, Moussa K. Photopolymerization of multifunctional monomers in condensed phase. *Journal of Applied Polymer Science*. 1987;34(4):1603–1618.
12. Luo Y, Le Fer G, Dean D, Becker ML. 3D printing of poly(propylene fumarate) oligomers: evaluation of resin viscosity, printing characteristics and mechanical properties. *Biomacromolecules*. 2019;20(4):1699–1708.
13. Scherzer T, Decker U. Real-time FTIR–ATR spectroscopy to study the kinetics of ultrafast photopolymerization reactions induced by acrylate monomers. *Vibrational Spectroscopy*. 1999;19(2):385–398.

14. Dulieu-Barton JM, Fulton MC. Mechanical properties of a typical stereolithography resin. *Strain*. 2000;36(2):81–87.
15. Puebla K, Wicker RB, Arcaute K. Effects of environmental conditions, aging, and build orientations on the mechanical properties of ASTM type I specimens manufactured via stereolithography. *Rapid Prototyping Journal*. 2012;18(5):374–388.
16. Dizon JRC, Espera AH, Chen Q, Advincula RC. Mechanical characterization of 3D-printed polymers. *Additive Manufacturing*. 2018;20:44–67.
17. Karalekas D, Aggelopoulos A. Study of shrinkage strains in a stereolithography cured acrylic photopolymer resin. *Journal of Materials Processing Technology*. 2003;136(1–3):146–150.
18. Huang YM, Jiang CP. On-line force monitoring of platform ascending rapid prototyping system. *Journal of Materials Processing Technology*. 2005;159(2):257–264.
19. Campanelli SL, Cardano G, Giannoccaro R, Lugarresi AD, Lugarresi G. Statistical analysis of the stereolithographic process to improve the accuracy. *Computer-Aided Design*. 2007;39(1):80–86.
20. Pilipovic A, Raos P, Sercer M. Experimental analysis of properties of materials for rapid prototyping. *International Journal of Advanced Manufacturing Technology*. 2009;40(1–2):105–115.
21. Vaezi M, Seitz H, Yang S. A review on 3D micro-additive manufacturing technologies. *International Journal of Advanced Manufacturing Technology*. 2013;67(5–8):1721–1754.
22. Leach R. *Characterisation of Areal Surface Texture*. Berlin: Springer; 2013.
23. Ligon SC, Liska R, Stampfl J, Gurr M, Mulhaupt R. Polymers for 3D printing and customized additive manufacturing. *Chemical Reviews*. 2017;117(15):10212–10290.
24. Bose S, Ke D, Saez H, Bandyopadhyay A. Bone tissue engineering using 3D printing. *Materials Today*. 2013;16(12):496–504.
25. Decker C. Photoinitiated crosslinking polymerisation. *Progress in Polymer Science*. 1996;21(4):593–650.
26. Zhu W, Ma X, Gou M, Mei D, Zhang K, Chen S. 3D printing of functional biomaterials for tissue engineering. *Current Opinion in Biotechnology*. 2016;40:103–112.

27. Menard KP. *Dynamic Mechanical Analysis: A Practical Introduction*. 2nd ed. Boca Raton (FL): CRC Press; 2008.
28. Cho YH, Lee IH, Cho DW. Laser scanning path generation considering photopolymer shrinkage in micro-stereolithography. *Microsystem Technologies*. 2005;11(2–3):158–167.
29. Singh R. Process capability study of polyjet printing for plastic components. *Journal of Mechanical Science and Technology*. 2011;25(4):1011–1015.
30. Briscoe BJ, Sinha SK. Wear of polymers. *Proceedings of the Institution of Mechanical Engineers Part J: Journal of Engineering Tribology*. 2002;216(6):401–413.
31. Mohanty S, Mahapatra SS, Routara BC, Satapathy A. Tribo-performance of glass/epoxy composites: analysis using Taguchi method and ANOVA. *Journal of Reinforced Plastics and Composites*. 2012;31(20):1366–1374.
32. Myshkin NK, Petrokovets MI, Kovalev AV. Tribology of polymers: adhesion, friction, wear and mass-transfer. *Tribology International*. 2005;38(11–12):910–921.
33. Bahadur S, Tabor D. The wear of filled polytetrafluoroethylene. *Wear*. 1984;98:1–13.
34. Friedrich K, Lu Z, Hager AM. Recent advances in polymer composites tribology. *Wear*. 1995;190(2):139–144.
35. Scharf TW, Prasad SV. Solid lubricants: a review. *Journal of Materials Science*. 2013;48(2):511–531.
36. Goldstein JI, Newbury DE, Michael JR, Ritchie NWM, Scott JHJ, Joy DC. *Scanning Electron Microscopy and X-Ray Microanalysis*. 4th ed. New York: Springer; 2018.
37. Newbury DE, Ritchie NWM. Is scanning electron microscopy/energy dispersive X-ray spectrometry (SEM/EDS) quantitative? *Scanning*. 2013;35(3):141–168.
38. Pantelic RS, Meyer JC, Kaiser U, Baumeister W, Plitzko JM. Graphene oxide: a substrate for optimizing preparations of frozen-hydrated samples. *Journal of Structural Biology*. 2010;170(1):152–156.
39. Dizon JRC, Gache HCC, Cascolan HMS, Cancino LT, Advincula RC. Post-process mechanical properties of 3D-printed polymers. *Technologies*. 2021;9(3):61.