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# Effect of process parameters on mechanical properties of photopolymeric resin in masked stereolithography

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**Abstract.** This study investigates the influence of process parameters on the mechanical properties and energy consumption of photopolymeric resins in the Masked Stereolithography (MSLA) 3D printing process. ELEGOO technology and resin were used to manufacture tensile specimens, according to ASTM D638-22 standards. The study employed a Full Factorial Design varying layer thickness (LT) and exposure time (ET) across three levels. Ultimate Tensile strength (UTS) and energy consumption were analyzed through experimental testing and nonlinear regression modelling. Results reveal that UTS decreases with increased LT, while higher ET enhances UTS. Energy consumption decreases as LT increases but rises with an increase of ET. Predictive models of UTS and Energy Consumption demonstrated high accuracy with $R^2$ values of 0.99 for both UTS and energy consumption, indicating their robustness in prediction process dynamics. These findings provide critical insights for optimizing MSLA printing to balance mechanical performance and energy efficiency.

## Introduction

Stereolithography (SLA), one of the most established additive manufacturing technologies, is based on the photopolymerization of liquid resins using UV light sources [1–4]. One of its most advanced variants is masked stereolithography (MSLA), which has gained popularity because of its ability to combine high precision, low cost and higher speed than other similar technologies, such as conventional SLA and DLP (Digital Light Processing) [5,6].

In the MSLA process, an LCD module acts as a digital mask, projecting the image of an entire model layer directly onto the surface of the photopolymer resin. This approach differs from traditional SLA, which uses a laser to track each section of the layer point by point, and DLP, which projects the entire image of the layer via a digital micro-mirror (DMD). In MSLA, the LED light source emits UV radiation through the LCD panel, which blocks or allows light to pass through only those areas corresponding to the section of the layer to be solidified [7].

This system allows uniform light distribution over the entire build area, improving production speed and reducing mechanical wear compared to laser scanning technologies. Each layer is built up by solidifying liquid resin only at the desired locations, and the process is repeated layer by layer until the three-dimensional object is complete.

The MSLA process allows for remarkable dimensional accuracy and a smooth surface finish, making it particularly suitable for industrial and biomedical applications, as well as industries such as aerospace and jewelry [1,8].

However, parameters such as exposure time, layer thickness and UV light intensity determine the quality of solidification and affect the mechanical and structural properties of the final component [9–11].

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Thus, a key element in ensuring the structural strength and repeatability of components lies in understanding the interactions between process parameters and the mechanical properties of the material. UV exposure time, for example, directly influences the degree of cross-linking of the polymer, modulating properties such as elastic modulus, tensile strength and deformation capacity [12].

Recent studies have shown that longer exposure times improve strength and stiffness but may reduce elongation at break, highlighting a trade-off in the optimal choice of parameters [7,13,14].

Layer thickness is another critical factor: thinner layers generally improve dimensional resolution and surface quality but can increase production time [15]. In addition, variations in UV light intensity affect the penetration and uniformity of solidification, with implications for the material's microstructure and mechanical properties.

Despite the wide use of MSLA for advanced applications, the literature points to the need for further studies to systematically characterize the mechanical properties of manufactured components and to optimize process parameters. The objective of this study is to analyze the combined effect of parameters such as exposure time and layer thickness on the tensile properties of standard specimens produced by MSLA, and evaluate the energy consumption related to the printing process.

The results of this research will not only improve the understanding of photopolymerization mechanisms and their consequences on mechanical properties, but also provide practical guidelines for optimizing manufacturing processes. This will expand the application possibilities of MSLA technology in critical industrial areas where a combination of high precision and optimized mechanical properties is required.

## Material and Methods

Material and technology. ELEGOO translucent standard commercial LCD photocurable resin used in vat photopolymerization AM technology was used as the material in this study. It consists mainly of epoxy acrylate resin and monomers and approximately 3-5% by weight of photoinitiators, according to the material data sheet. The tensile strength of the photocurable resin provided by the manufacturer is between 36-53 MPa.

The ELEGOO Saturn 4 Ultra LCD 3D printer uses Masked Stereolithography (MSLA) technology, which masks UV LED lights with a selectively transparent LCD screen to precisely cure resin layers. As the UV light passes through the unmasked areas, the resin hardens to form the object's layer. This process occurs layer by layer: as each layer is completed, the build platform in the resin tank rises slightly to allow fresh resin to cover the new layer. The projection and curing process continues until the entire object is printed. Each layer is precisely constructed thanks to the projector's ability to quickly and evenly illuminate complex areas. After printing, the object is removed from the tank and subjected to a post-curing process to ensure that all parts are fully cured. This includes a solvent wash to remove any residual uncured resin and exposure to additional UV light. In particular, in this study after the printing process the parts were washed in isopropyl alcohol for 5 min and post-cured via UV lights for 5 min.

The dedicated washing and curing machines (ELEGOO Mercury X Bundle) were used. In the Fig. 1 are reported the machine used for the printing and post-curing processes.




**Elegoo Saturn 4 Ultra** **Elegoo Mercury X - Bundle**

*Figure 1 – 3D printed and post-curing machines used*

Tensile test. Dog bone specimens were prepared to evaluate the tensile properties pure resin in accordance with ASTM D638-22 standard for plastics (Type IV specimens). The specimens were characterised by a constant nominal thickness, gauge length and width of 3.6, 33 and 6 mm respectively, as shown in Fig. 2. A minimum of five specimens for each configuration were tested using the MTS 810® universal servo-hydraulic testing machine. Tensile tests were performed at a constant crosshead speed of 5 mm/min. During the tests, load and strain along the loading direction were recorded using a 25 kN load cell and extensometer and plotted as tensile stress-strain curves to derive the ultimate tensile strength (UTS) as a function of process parameters.

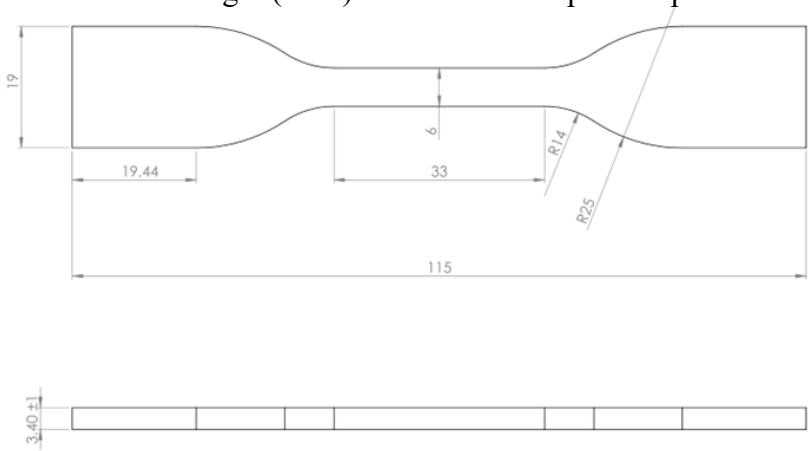



*Figure 2 – Type IV specimen of ASTM D638-22 standard. All dimensions are in mm.*

The printing parts are influenced by several preprocessing factors, including layer thickness, build orientation, and normal exposure time. Additionally, postprocessing factors such as washing time, and curing time also play a role. The parameters are selected based on a review of the relevant literature and their significance.

Layer Thickness (LT), and Exposure Time (ET) are the investigated process parameter and a three level Full Factorial Design (FFD) was performed. It means that 2 control factors are considered, LT and ET, each at 3 level. These are referred to as low, intermediate, and high level. Table 1 and Table 2 report control factors, the respective levels, and the investigated condition.

*Table 1 – Control factors and their levels*

| | | Value levels | | |
|---|---|---|---|---|
| Parameters | Units | Low (1) | Medium (2) | High (3) |
| Exposure time (ET) | s | 4 | 8 | 12 |
| Layer Thickness (LT) | mm | 0.01 | 0.05 | 0.09 |

*Table 2 – Printed and tested condition according to three level FFD*

| | Actual level of variables | | Coded level of variables | |
|---|---|---|---|---|
| Run no. | ET [s] | LT [mm] | ET [s] | LT [mm] |
| 1 | 4 | 0.01 | 1 | 1 |
| 2 | 4 | 0.05 | 1 | 2 |
| 3 | 4 | 0.09 | 1 | 3 |
| 4 | 8 | 0.01 | 2 | 1 |
| 5 | 8 | 0.05 | 2 | 2 |
| 6 | 8 | 0.09 | 2 | 3 |
| 7 | 12 | 0.01 | 3 | 1 |
| 8 | 12 | 0.05 | 3 | 2 |
| 9 | 12 | 0.09 | 3 | 3 |

The other printing and post-cure variables that could affect the mechanical properties of the printed parts are kept constant, and reported in Table 3. In addition, the samples were printed in the same direction (i.e. flat on the building plate). Also, during each printing process the energy consumption was measured by using a power meter.

*Table 3 – Other process parameters kept constant*

| Process Parameter | Value |
|---|---|
| Light Intensity | 100% |
| Bottom Layer | 3 |
| Bottom Exposure Time | 30 s |
| Post Curing Time | 5 min |
| Washing Time | 5 min |

Finally, a non-linearmultiple regression (Eq. 1) was performed to derive the UTS and Energy consumption as function of Layer Thickness and Exposure Time:

$$y = f(x_1, x_2, \dots, x_n), \tag{1}$$

where $x_1, x_2, \dots, x_n$ and $y$ represent input and outp.ut variables, respectively.

The least-squares method was used for the multiple regression. Non-linear MR was performed to obtain reliable results. The goal is to find the best-fitting curve that minimizes the sum of squared residuals between the observed and predicted values. A model based on second-order equation (Eq. 2) is used to explain this relationship.

$$y = b_0 + \sum_{i=1}^{m} b_i x_i + \sum_{i=1}^{m-1} \sum_{j \geq i}^{m} b_{ij} x_i x_j + \sum_{i=1}^{m} b_{ii} x_i^2 + \varepsilon, \tag{2}$$

In the equation, i represents the linear coefficient, j represents the second order coefficient, b represents the regression coefficient, m represents the number of parameters, and ε represents the error identified in the response.

This method is generally used to predict dependent variables based on the values of independent variables. Specifically, in the present study, the UTS and energy consumption were predicted using

Minitab software to perform multiple regression analysis. To assess the fit of the analytical model R-squared ($R^2$), adjusted R-squared ($R^2adj$), and mean square error (MSE) were used. $R^2$ and $R^2adj$ measure the proportion of variation in the response variable explained by the independent variables, while MSE indicates how well the regression model fits the data. However, it is essential to consider not only the $R^2$ values but also their adjusted counterparts. The adjusted $R^2$ modifies the $R^2$ statistic to account for the number of predictors in the model and the sample size. This adjustment is crucial, particularly in complex models with multiple independent variables, as it helps prevent overestimating model accuracy. In an ideal model, the values for $R^2$ and $R^2adj$ would be 100%, and the value for MSE would be 0. The closer the values of these fit indicators are to these ideal values, the better the model's fit to the data.

**Results and Discussion**

In order to evaluate the effect of the LT and ET on the UTS of MSLA-printed parts and to obtain the relationship between input and output, tensile specimens printed at different conditions were tested at room temperature. Furthermore, the effect of LT and ET on Energy consumption was investigated. To this purpose, Fig. 3 shows the effect of process parameters on the typical stress-strain curves and specimens after tensile tests.

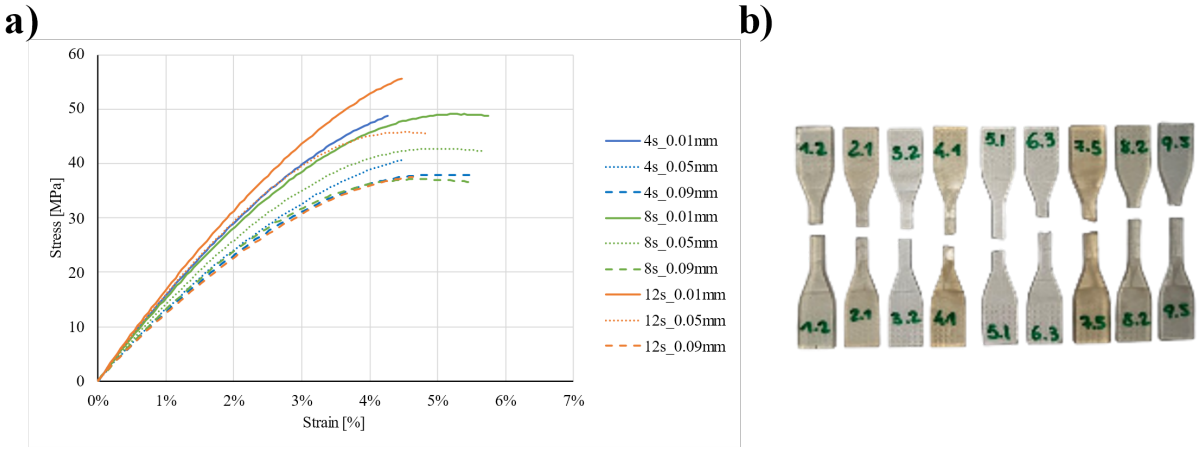



*Figure 3 – Effect of ET and LT on: a) typical stress-strain curves, and b) specimens after tensile tests*

Figure 3a shows that the tensile stress linearly increases with strain in the elastic region until yielding; then, the stress rises with a non-linear behaviour up to a peak value at which necking occurs (UTS). Finally, the stress decreases with increasing strain until failure. It can be observed that the process parameters affect the mechanical properties of the printed specimens. As far as the effect of layer thickness is concerned, for a given strain value in percentage, the tensile strength increases with decreasing LT. Such behaviour can be attributed to the more effectiveness of the curing process and at the improved cohesion between layers at low thickness values. As regards the effect of exposure time on the mechanical performances of the tensile specimens, it can be noted that the tensile strength rises with exposure time values. The result is due to the longer duration of the curing process, as well as the more energy applied to each layer, with the same thickness.

Table 4 summarizes the values of UTS, energy consumption after printing and post-curing processes, and printing time values evaluated at every condition investigated. The results show that the process parameters investigated affect, in addition to the mechanical properties, also the energy consumption and printing time. Specifically, by keeping the exposure time constant, both the UTS, energy consumption and printing time decrease as the layer thickness increases. On the contrary, the UTS, energy consumption and printing time increase with the exposure time, by keeping the layer thickness constant.

*Table 4 – UTS, Energy Consumption and printing time at different printing condition*

| Conditions | Exposure Time [s] | Layer Thickness [mm] | UTS [MPa] | Energy Consumption [KWh] | Printing Time [h] |
|---|---|---|---|---|---|
| 1 | 4 | 0.01 | 48.1 ± 0.53 | 0.09 | 0.92 |
| 2 | 4 | 0.05 | 40.7 ± 2.10 | 0.03 | 0.26 |
| 3 | 4 | 0.09 | 37.2 ± 1.61 | 0.02 | 0.19 |
| 4 | 8 | 0.01 | 49.1 ± 1.93 | 0.12 | 1.27 |
| 5 | 8 | 0.05 | 42.8 ± 2.01 | 0.04 | 0.34 |
| 6 | 8 | 0.09 | 37.4 ± 2.5 | 0.03 | 0.22 |
| 7 | 12 | 0.01 | 55.7 ± 2.05 | 0.16 | 1.63 |
| 8 | 12 | 0.05 | 45.8 ± 1.11 | 0.05 | 0.39 |
| 9 | 12 | 0.09 | 37.6 ± 1.6 | 0.04 | 0.26 |

The outputs of the non-linear multiple regressions are represented in Eq. 3 and Eq. 4, where the UTS and energy consumption are expressed as a function of Layer thickness (LT), Exposure Time (ET).

$$\mathrm{UTS} = 48.06 - 0.011 \cdot \mathrm{TE} - 142.7 \cdot \mathrm{LT} + 0.07 \cdot \mathrm{TE}^2 + 613 \cdot \mathrm{LT}^2 + 11.09 \cdot \mathrm{LT} \cdot \mathrm{ET}, \quad (3)$$

$$\mathrm{KWh} = 0.09 + 0.08 \cdot \mathrm{TE} - 2.85 \cdot \mathrm{LT} + 0.00005 \cdot \mathrm{TE}^2 + 23.9 \cdot \mathrm{LT}^2 - 0.084 \cdot \mathrm{LT} \cdot \mathrm{ET}, \quad (4)$$

Figure 4 shows the trends of UTS and energy consumption as function of LT and ET retrieved by using Eq. 3, and Eq. 4. In Figure 4a it is possible to note that the UTS decreases as the LT increases for each ET value, since for the same layer height, the curing process will be more complete as layer thickness decreases. Moreover, by increasing the layer thickness while keeping the exposure time constant, there will be reduced bonding of the printed layer with the underlying one. As a result, the cohesion between layers will decrease, leading to higher porosity in the part. Reduced interlayer adhesion, resulting in a decline in the overall mechanical strength of the part. Also by keeping the LT constant, UTS grows as the ET increases, since for the same layer thickness, ET plays a critical role in determining the quality of the interlayer bonding in MSLA processes. A higher ET corresponds to a longer duration during which energy is applied to cure each layer. This extended exposure allows for improved cohesion between layers, effectively reducing the presence of porosity and defects. Additionally, the stronger bonding achieved enhances the cohesion between consecutive layers, which translates into an increase in the UTS of the printed part.

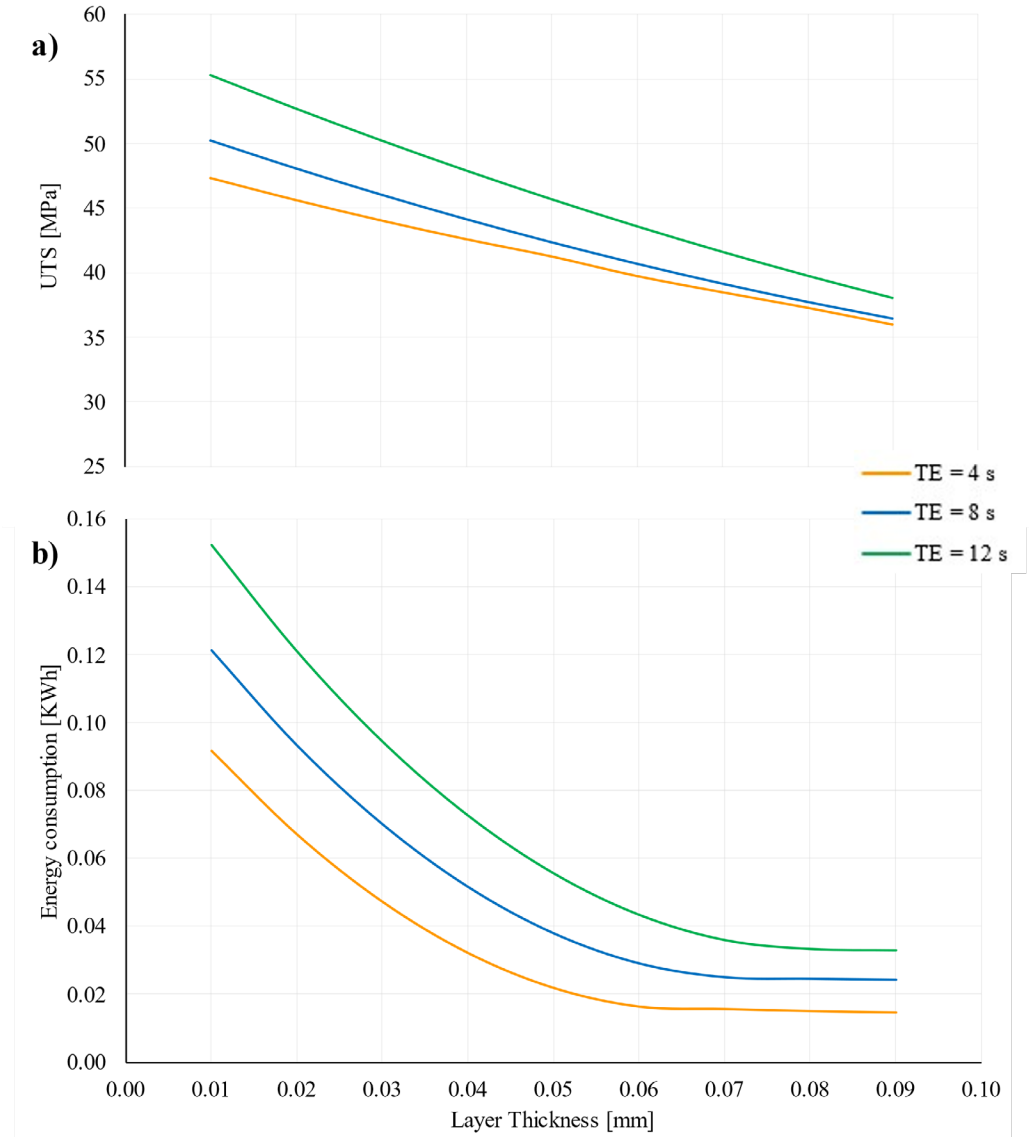



*Figure 4 – (a) UTS and (b) energy consumption trends obtained by the mathematical model*

The energy consumption in MSLA processes is influenced by both the layer thickness and the exposure time, as shown in Figure 4b. When the layer thickness increases, the total number of layers required to build the part decreases. This reduction in the number of layers leads to a shorter overall processing time and, consequently, a lower energy requirement to complete the part, even though the individual layers are thicker. This relationship shows the observed decreasing trend in energy consumption as the layer thickness increases.

More energy is applied per unit of surface area or layer due to the longer duration of energy exposure. As a result, each layer consumes more energy. Although increasing the layer thickness reduces the total number of layers, the higher energy input per layer caused by longer ET offsets this effect, leading to an overall increase in energy consumption.

Subsequently, in order to evaluate the robustness of the mathematical model, the experimental results obtained by the tensile tests were compared with the values predicted by the models in the same printing conditions.

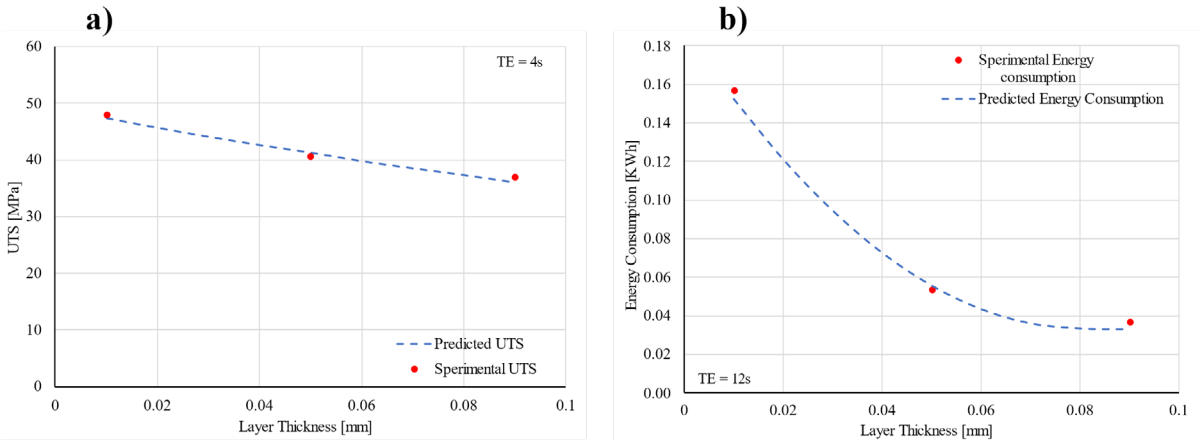



*Figure 5 – Comparison between the experimental and predicted (a) UTS and (b) energy consumption values*

The accuracy of the mathematical model in predicting the values of UTS (Ultimate Tensile Strength) and energy consumption as a function of Layer Thickness (LT) and Exposure Time (TE), as shown in the graphs, is satisfactory.

In the Figure 5a related to UTS, the experimental data (indicated by the red dots) clearly show a decreasing trend as the layer thickness increases. The blue dashed line, representing the predicted values from the mathematical model, closely follows the experimental trend, with slight discrepancies at low layer thicknesses (LT < 0.02 mm). Although this discrepancy is present, it is minimal and does not significantly compromise the model's validity. The good correspondence between the experimental data and the predicted values confirms the model's accuracy in predicting the UTS trend as a function of layer thickness, with a relatively low error.

In the Figure 5b related to energy consumption, the blue dashed line, representing the predicted values, overlaps almost perfectly with the experimental data, with the red dots closely following the curve. Again, the model correctly predicts the decreasing trend of energy consumption as the layer thickness increases. The small variations between the experimental data and the predicted values are minimal and can be attributed to uncontrollable variables or imperfections in the experimental process, but they do not significantly affect the model's reliability.

Overall, the model's accuracy is high, with good correlation between the experimental and predicted data, suggesting that the mathematical model effectively describes the process dynamics. The low level of error observed indicates that the model can be confidently used to predict UTS and energy consumption as a function of process parameters. In Table 5 are reported the values of robustness indicators.

*Table 5 – Values for robustness indicator for mathematical models*

| | $R^2$ | $R^2_{adj}$ | MSE | Ref. |
|---|---|---|---|---|
| UTS model | 99.13% | 98% | 0.429 $MPa^2$ | Eq. 3 |
| Energy Consumption model | 99.03% | 97% | 3 * $10^{-5}$ $kWh^2$ | Eq. 4 |

For the UTS prediction model, an impressive $R^2$ value of 99% was obtained. This indicates that 99% of the variability in UTS can be accounted for by the model, signifying an exceptional fit to the data. Such a high $R^2$ value suggests that the model is highly effective in capturing the underlying relationships present in the dataset. For the energy consumption prediction model yielded an $R^2$ value of 99%. This value still reflects strong predictive capability, indicating that 99% of the variability in energy consumption is explained by the model. Both models demonstrate a robust ability to predict their respective outcomes.

For the UTS model, while the adjusted $R^2$ will be slightly lower than 98%, it remains close enough to suggest that adding more variables does not significantly contribute to overfitting. This indicates a well-balanced model that retains its predictive power without unnecessary complexity. Similarly, for the energy consumption model, the adjusted $R^2$ will also be marginally lower than 97%. Although this reduction may be more pronounced with an increased number of predictors, it still reflects a robust performance. In examining the mathematical models, it is anticipated that the Mean Squared Error (MSE) will be very low, consistent with the high $R^2$ values observed. This suggests that there are minimal discrepancies between the observed values of UTS and energy consumption and those predicted by the models. A low MSE reinforces confidence in the predictive capabilities of these models.

## Conclusion

This study demonstrated how process parameters, particularly layer thickness (LT) and exposure time (ET), significantly influence mechanical strength and energy consumption in MSLA printing processes. The main outcomes of this work are reported as follows

- Decreasing LT enhances interlayer cohesion, leading to increased tensile strength (UTS), while higher ET further improves cohesion by reducing defects and porosity;
- Energy consumption exhibits an inverse behaviour, decreasing with increased LT and increasing with longer exposure times;
- The mathematical model, which correlate the Ultimate Tensile Strength and Energy consumption to the process parameter, is retrieved by performing a second order non-linear multiple regression;
- The predictive models developed showed high reliability, with $R^2$ values of 0.99, proving their usefulness for accurate forecasting of mechanical and energy-related outcomes. The low value of Mean Squared Error also demonstrate the goodness of the mathematical model.
- These findings are crucial for optimizing MSLA printing processes, enabling more sustainable and efficient production.

The analysis underscores the potential applications in relevant fields where accurate predictions are essential for decision-making and further research. The validation of the models could be further strengthened by future studies with larger datasets and diversified operating conditions.

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