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# Dimensional Accuracy of CNTs/PMMA Parts and Holes Produced by Laser Cutting

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***Abstract*****—**Laser cutting is a very common production method for cutting 2D polymeric parts. Developing of polymer composites with nano-fibers makes important their other properties like laser workability. The aim of this research is investigation of the influence different laser cutting conditions on the dimensional accuracy of parts and holes from poly methyl methacrylate (PMMA)/carbon nanotubes (CNTs) material. Experiments were carried out by considering of CNTs (in four level 0,0.5, 1 and 1.5% wt.%), laser power (60, 80, and 100 watt) and cutting speed 20, 30, and 40 mm/s as input variable factors. The results reveal that CNTs adding improves the laser workability of PMMA and the increasing of power has a significant effect on the part and hole size. The findings also show cutting speed is effective parameter on the size accuracy. Eventually, the statistical analysis of results was done, and calculated mathematical equations by the regression are presented for determining relation between input and output factor.

***Keywords*****—**Dimensional accuracy-PMMA-CNTs-laser cutting.

## I. Introduction

$CO_2$ laser cutting is one of the most common methods in order to product 2D polymeric parts [1]. Advantages like no requiring special tool, lake of tool wear, no vibration and no clamping ,high production speed and easy utilization due to the flexible manufacturing system cause that the laser cutting is known as the more applicable nontraditional machining [2]-[4]. In order to produce high quality and accurate parts, different researches and investigations were carried out for precise and better controlling of this process [5]-[8]. Heat affected zone (HAZ), height of burr, cut surface roughness, average kerf width, depth of laser penetration, angle of cut edge, mechanical properties and dimensional deviation are the investigable outputs in this process [1]-[10]. Due to the application effects, dimensional accuracy is an important output that was rarely attended by researches [4]. On the other hand, obtaining the precise dimensions is a hard challenge in laser cutting process. In this process, the width of cut path (effect point of laser beam) is widely depended on the type of under cutting material. Moreover, the variable input parameters like power and cutting speed have the essential role on the cut path width [4], [11]-[13]. Cutter Radius Compensation, also known as CRC, is a function of the computer numerical control (CNC) to automatically shift the tool from the cutter center line to the cutter edge along the programmed cutter path in the CNCs machining processes, because the tool radius is definite [14]. Therefore, using of CRC system is not feasible in laser cutting process, and for producing the accurate parts and holes, the input factor rolls should be studied.

It seems that adding of some special nano-fibers within the under cutting materials can assist to control the part precise. In this way, CNTs have a special effect on the thermal properties of polymers [15]-[18]. Therefore, utilization of CNTs can be useful [19].

This paper is attempting to investigate the role of variable laser processing parameters on the dimensional accuracy of the parts and holes. The selected material to investigate is PMMA. Study of the CNTs adding effects to the PMMA to control the dimensional accuracy is the second focus of this paper.

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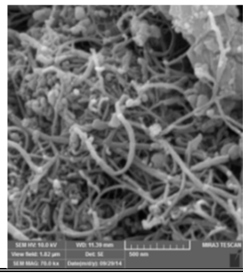
## II. Materials and Set Ups

### A. Materials

In this study, PMMA pellets were purchased from CHI MEI- CM205 Corporation (Taiwan). The CNT is also purchased from Nanostructured & Amorphous Materials Inc. (Texas, USA) which has been produced by the chemical vapor deposition (CVD) method. The properties of used material were tabulated in Table I.

TABLE I
The Properties of Materials

| PMMA properties | CNT Properties |
|---|---|
| Melt flow index (MFI)= 11 g/10 min | Outside diameter = 30-50 nm |
| Density =1.19 g/cm$^3$ | Inside diameter = 5-15 nm |
| Izod Impact Strength(180/1A- Notched)= 2 kJ/m$^2$ | Length = 10-20 µm |
| Tensile Elongation (50 mm/min)= 10% | Purity= >95% |
| Tensile Strength (50 mm/min-yield)= 73 MPa | Density is 2.1 g/cm$^3$ |
|   |  |

### B. Nanocomposite Sheets

Extrusion method was used for mixing the MWCNT/PMMA pellets. First, both PMMA and CNTs are dried for 4 hours at 80 °C in the oven. Then, CNTs and

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PMMA are mixed physically together in different weight percentage of CNTs (0.5, 1 and 1.5 wt. %). A ZSK25 co-rotating twin-screw extruder was used for mixing the MWCNT/PMMA pellets. The screws speed of the extruder was set at about 250 rpm, and barrel zones temperatures were set as 200, 210, 230, 225, 230 and 2200 °C. Then, the extruded blends of PMMA/MWCNT are cut into pellets. Due to the water using as a coolant in extrude step, the PMMA/MWCNT pellets absorb water. For eliminating thewater from the pellets, a drying step is followed after extruding for 24 hours at 80 °C.

In the next stage, in order to turn the pellets to nanocomposite sheets, a mold by a cavity with dimension of 175 × 80 × 3 mm is used. The sheets are produced using an NBM HXF-128 plastic injection molding. This step machine's setups are shown in Table II. The SEM micrographs from cross section of different produced nanocomposites are represented in Fig. 1. Accordingly, the dispersion of CNTs within the polymer matrix is satisfying, and agglomeration points are low.

TABLE II
INJECTION MOLDING MACHINE SETUPS

| Parameter | Unit | Amounts |
|---|---|---|
| **Injection pressure** | Bar | 80 |
| **Holding pressure** | Bar | 60 |
| **Barrels temperature** | ºC | 220 – 235 – 250 – 250 |
| **Injection speed** | mm/sec | 100 |
| **Cooling time** | Sec | 12 |
| **Holding time** | Sec | 5 |

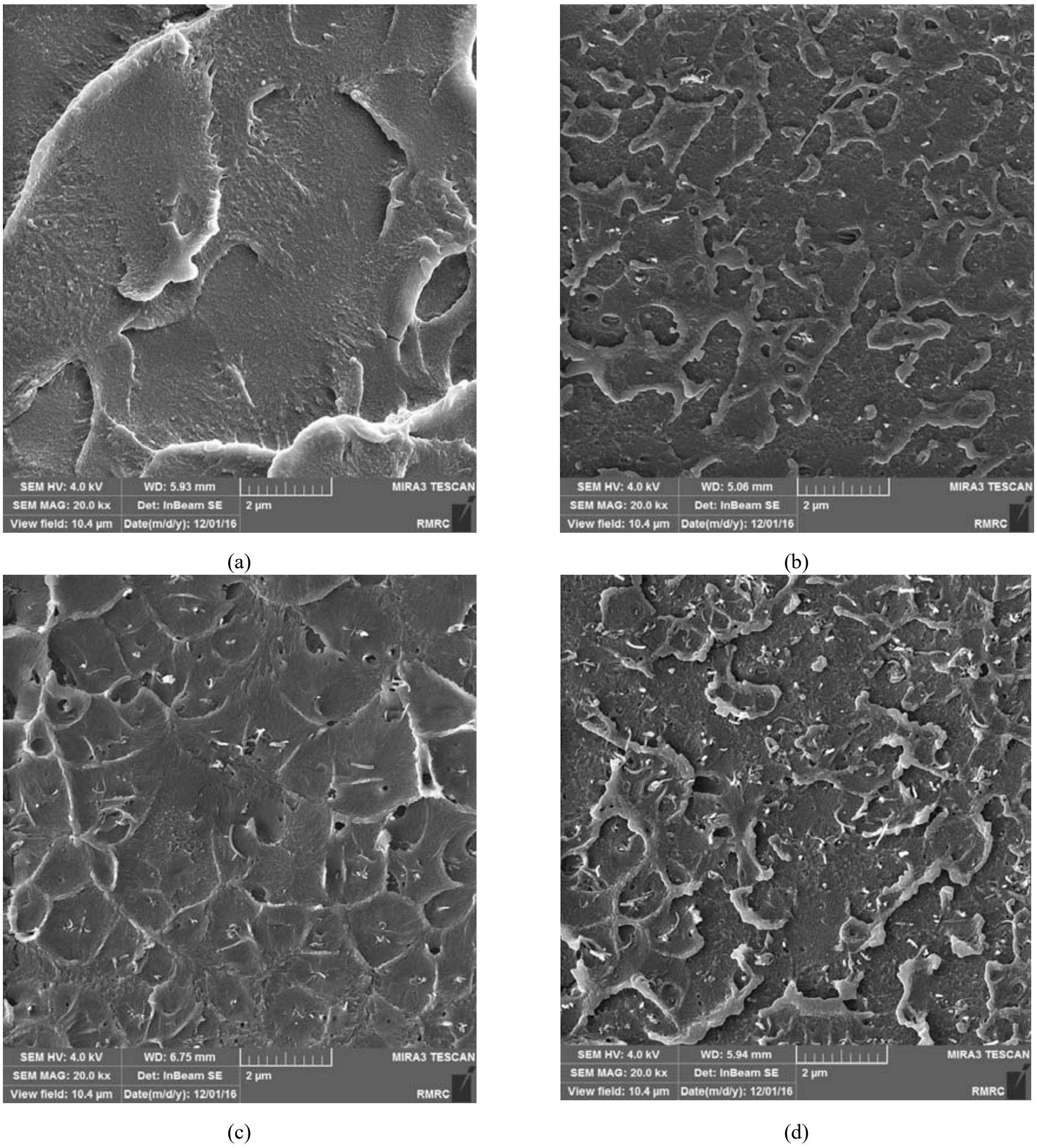



Fig. 1 SEM pictures from samples cross section (a) neat PMMA (b) MWCNTs= 0.5% wt. (c) MWCNTs= 1% wt. (d) MWCNTs= 1.5% wt

### C. Laser Cutting Process

Laser cutting tests are carried out using a laser system consisting of 100 W continuous $CO_2$ laser (YM Laser Machine PN1380), two axes CNC controlled table with the work volume of 1300 × 800 mm. Three parameters, percentage of CNTs (in four levels), laser power (in three levels) and cutting speed (in three levels) are considered as the variable parameter of laser cutting process. The compressed air was used as covering gas with 0. 28 bar pressure. Focal point is fixed on the middle of the work piece. Type of used lens was stable and its ideal cutting width was 0.2 mm. Table III shows the variable parameters and their levels. Designs of experiment (DOE) are used by full factorial method, and every experiment run is replicated three times. After laser cutting, part and created holes are two available cases to study (according to Fig. 2) which were investigated in this research. For measurement of cut parts and holes dimension, digital caliper (mitutoyo-Japan) by the resolution of 0.01 mm was used.

TABLE III
LEVELS OF THE PROCESSING PARAMETERS OF THIS RESEARCH

| parameters | Symbol | Levels of the processing parameters of this research Levels | | | |
|---|---|---|---|---|---|
| CNTs (wt %) | C | 0 | 0.5 | 1 | 1.5 |
| Laser Power (watt) | P | 60 | 80 | 100 | - |
| Cutting speed (mm/s) | S | 20 | 30 | 40 | - |

## III. RESULTS AND DISCUSSION

Fig. 3 shows the effect of laser power and CNTs concentration on the dimensional deviation of cut parts (P-dimensional deviation). As can be seen, the power increase has a bad effect on dimension accuracy of parts. The laser power is a deciding factor on the heat generation in laser cutting process [1]. When the laser power is enhanced, the amount of heat goes up, consequently the volume of materials in the cut path is increased. Eventually, the width of cut is developed, and these conditions prepare the decrease of dimensional accuracy. In addition, the waviness and edges destruction decrease by power decreasing. This phenomenon is clear in the microscopic images that were represented in Fig. 4. The improvement of cut edge by increasing of cutting speed and CNTs concentration was observed in microscopic studies. It seems that all conditions which lead to rapid heat transfer or lower heat generations decrease the waviness and roughness of cut edge, thereby better dimensional accuracy is produced. So, it can be concluded that, if the part is needed after cutting, for reaching better accuracy and precision, the lowest possible power can be recommended.

According to the obtained results, the effect of CNTs on the dimensional accuracy is positive. The CNT concentration increasing causes to decrease the dimensional deviation. For discussing this finding, the effect of CNTs on the thermal properties of matrix polymer should be studied. In general vision, laser process depends directly on the thermal properties of under cutting workpiece material [20]. The adding of CNTs within the polymers increases its thermal conductivity that different papers reported this matter [15], [21], [22]. When the thermal conductivity is increased, the generated heat in the laser cutting process is transferred rapidly and the time is decreased for developing of kerf [1], [19]. In the other words, the thermal diffusivity which is deciding parameter on heat transfer speed, is diminished by thermal conductivity reduction [23]. Therefore, the better cutting properties are made by adding of CNTs. Increasing of CNTs concentration also improves the discussed conditions.

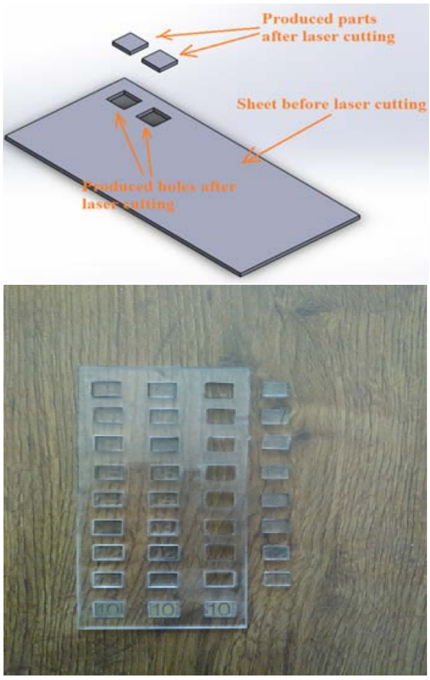



Fig. 2 The produced parts and holes after laser cutting

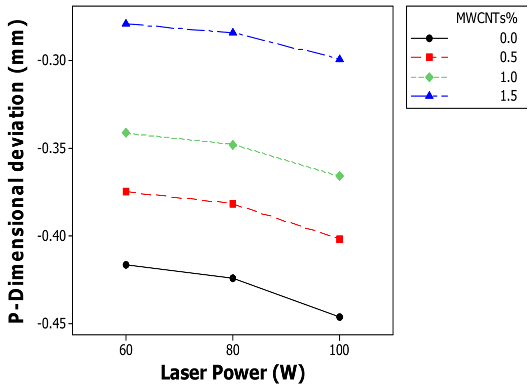
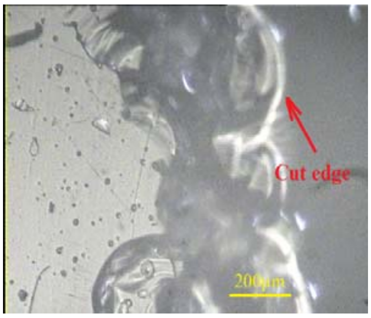
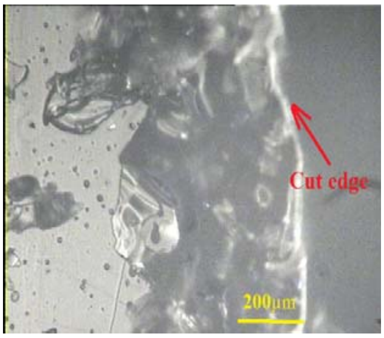


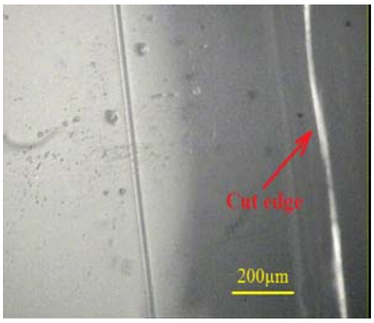

Fig. 3 Effect of the laser power and CNT concentration on the part dimensional accuracy




(a)




(b)




(c)

Fig. 4 Microscopic images from cut edge for specimens by MWCNTs 0.5 wt.%. (a)power=60 W (b)power=80 W (c)power= 100 W

The effect of cutting speed and CNTs concentration on the P-dimensional deviation is shown in Fig. 5. As it is evident from Fig. 5, using of higher cutting speed improves the dimensional accuracy. The cutting speed is a parameter that determines the contact time between laser beam and sample [1]. When high cutting speed is used to cut, the contact time between laser beam and specimen is fixed in low amount and consequently input heat decreases. This phenomenon makes the narrower kerf by diminishing the melting volume that results better precise. Finally, it can be concluded that, in the case of part cutting for obtaining the better dimensional accuracy, the power should be set at the lower amount and the cutting speed also should be considered in the highest feasible value.

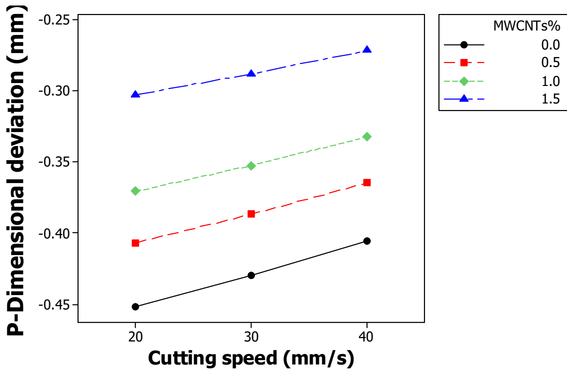



Fig. 5 Effect of the cutting speed and CNT concentration on the part dimensional accuracy

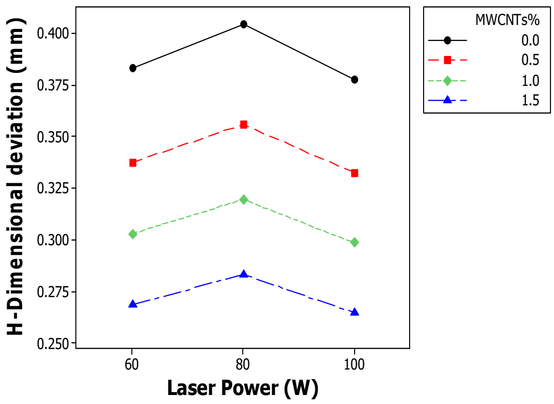



Fig. 6 Effect of the laser power and CNT concentration on the hole dimensional accuracy

The influence of laser power and CNTs percentage on the hole dimensional deviation is depicted in Fig. 6. As can be seen in this figure, the present CNTs limit the dimensional deviation and improve the laser cutting workability of PMMA. As it was described, this finding is due to the effect of thermal properties altering which was occurred. The remarkable points in this figure are the effect of power. The minimum deviation is obtained for maximum power, but when the power increases from 60 to 80 W, the deviation increases, inordinate power increasing from 80 to 100 W decreases the deviation. In the laser cutting process, two major mechanisms exist; the first is melting mechanism and the second is direct evaporation from solid state to gas form. In the low power, the melting mechanism is dominant, but when the power is enhanced inordinately, the direct evaporation mechanism is stronger. In general, the evaporation mechanism creates better condition. Fig. 7 represents the effect of the cutting speed and CNTs percentage on the H-dimensional deviation. It is observed that like P-dimensional deviation, cutting speed increasing conducts the deviation to zero.

Finally, the lowest H-dimensional deviation is achievable by the utilization of the maximum feasible power and cutting speed.

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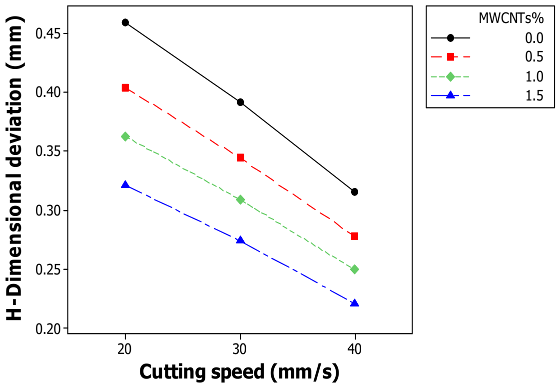


Fig. 7 Effect of the cutting speed and CNT concentration on the hole dimensional accuracy

## IV. Regression

The regression model to represent the mathematic model among P-dimensional deviation and various controllable input parameters of this research has been developed by regression analysis [24]. Due to the significant effect of all input parameters, the regression equation of P-dimensional deviation was taken as a function of MWCNT concentration, laser power, and cutting speed.

Tables IV and V indicate the estimated regression coefficients. The calculated equation from regression is present in the first row of Tables IV and V, where C is the CNT concentration (%), P is the laser power (W), and S is the cutting speed (mm/s). The P-value amounts are less than α-level (0.05). It reveals all of picked terms are effective. The R-Squared is defined as the ratio of variability explained by the model to the total variability in the actual data and is used as a measure of the goodness of fit. The more R-sq approaches unity, the better model fits the experimental data. The value of R-sq(predicted) indicates the prediction capability of the regression model. All of the calculated R-sq are more than 90%, which displays that the considered models have a high adequacy.

Analysis of variance (ANOVA) for the adequacy of the model is shown in Tables VI and VII. The comparison between theory F and calculated F exhibits that the terms and regression model have high accuracy. Also, Durbin-Watson Statistics for equations of Tables VI and VI were obtained 1.766 and 1.418, respectively that it eventuates autocorrelation. Another model precision characteristic is percentage of differential between regression and experimental results that it was defined as the $D_P$. Two models are enjoyed with very low $D_P$, therefore they have an acceptable precision.

TABLE IV
Estimated Regression Model and Coefficients for P-Dimensional Deviation Results

| Regression Equation | P-Dimensional deviation (mm) = -0.44117 + 0.09186 **C** - 0.00063**P** +0.001977 **S** | | | |
|---|---|---|---|---|
| Term | Coef | SE Coef | T | P |
| Constant | -0.441168 | 0.0114349 | -38.5810 | 0.000 |
| C% | 0.091861 | 0.0032222 | 28.5088 | 0.000 |
| P (W) | -0.000636 | 0.0001103 | -5.7624 | 0.000 |
| S (mm/s) | 0.001978 | 0.0002206 | 8.9638 | 0.000 |
| S = 0.0108076 R-Sq = 96.66% R-Sq(adj) = 96.35% PRESS = 0.00472671 R-Sq(pred) = 95.78% | | | | |

TABLE V
Estimated Regression Model and Coefficients for H-Dimensional Deviation Results

| Regression Equation | H-Dimensional deviation (mm) = 0.556696 - 0.0738156 **C** - 0.00584347 **S** | | | |
|---|---|---|---|---|
| Term | Coef | SE Coef | T | P |
| Constant | 0.556696 | 0.0133402 | 41.7309 | 0.000 |
| C% | -0.073816 | 0.0059107 | -12.4884 | 0.000 |
| S (mm/s) | -0.005843 | 0.0004047 | -14.4397 | 0.000 |
| S = 0.0198252 R-Sq = 91.70% R-Sq(adj) = 91.19% PRESS = 0.0155047 R-Sq(pred) = 90.08% | | | | |

TABLE VI
Analysis of Variance for P-Dimensional Deviation's Regression Model

| Source | DF | Seq SS | Adj SS | Adj MS | F | P | Percent effect |
|---|---|---|---|---|---|---|---|
| Regression | 3 | 0.108 | 0.108 | 0.0360 | 308.7 | 0.00 | 25 |
| C% | 1 | 0.094 | 0.095 | 0.0949 | 812.7 | 0.00 | 65.8 |
| P (W) | 1 | 0.003 | 0.004 | 0.0038 | 33.20 | 0.00 | 2.68 |
| S(mm/s) | 1 | 0.009 | 0.009 | 0.0094 | 80.35 | 0.00 | 6.5 |
| Error | 32 | 0.003 | 0.003 | 0.0001 | | | |
| Total | 35 | 0.112 | | Durbin-Watson statistic = 1.766 Dp=0.0155 | | | |

TABLE VII
Analysis of Variance for H-Dimensional Deviation's Regression Mo del

| Source | DF | Seq SS | Adj SS | Adj MS | F | P | Percent effect |
|---|---|---|---|---|---|---|---|
| Regression | 2 | 0.143249 | 0.143249 | 0.0716245 | 182.232 | 0.00 | 33.31 |
| C% | 1 | 0.061298 | 0.061298 | 0.0612983 | 155.959 | 0.00 | 28.5 |
| S(mm/s) | 1 | 0.081951 | 0.081951 | 0.0819508 | 208.505 | 0.00 | 38.11 |
| Error | 33 | 0.012970 | 0.012970 | 0.0003930 | --- | --- | --- |
| Lack-of-Fit | 9 | 0.001180 | 0.001180 | 0.0001311 | 0.267 | 0.97 | 0.060 |
| Pure Error | 24 | 0.011791 | 0.011791 | 0.0004913 | --- | | --- |
| Total | 35 | 0.156 | Durbin-Watson statistic = 1.418, Dp=0.0000 | | | | |

## V. Conclusion

The dimensional accuracies of parts and holes produced by laser cutting from CNTs/PMMA material were evaluated. To reach this aim, the laser power and cutting speed were considered as variable factors. The obtained results reveal that:

- Adding of CNTs as a fiber within the PMMA matrix improves its laser cutting workability.
- The accurate and precise part can be produced, when the laser power and cutting speed were set at the lowest and the highest feasible values. It should be recommended

that, according to the statistical analysis, the cutting velocity is more effective than laser power.

- When the power and cutting speed are considered at the maximum possible amounts, the holes can be cut at the least dimensional errors.

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