# Some quality in aspects of microdrilling using $CO_2$ pulsed laser

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Micro machining have reached a stage of development that allows wide scale application in different fields including information and communication technology, automotive and space industries, biochemical engineering and medical technology. $CO_2$ laser is considered as one of the most established techniques applied in industrial applications. Quality and surface integrity of laser machined components are affected by the processing parameters together with the type and thickness of the material to be machined. This study considers some quality aspects of micro holes produced on ACRYLIC sheets using pulsed $CO_2$ laser. The effect of some process parameters (e.g. laser power, speed, feed rate, and pulse intensity) on produced features quality is investigated using a design of experiments approach. The main quality characteristics considered in this study are the average diameter, concity, roundness and protrude of the micro-drilled holes. A vision-based technique was applied to evaluate the dimensions and form errors of produced holes. Four empirical models were developed to relate the estimated quality characteristics with the selected process parameters.

لقد وصلت عمليات التشغيل الدقيق مرحلة من التقدم اتاحت مجالا واسعا لاستخدامها فى العددي من التطبيقات من بينها: تقنيات المعلومات والاتصالات، صناعة السيارات والصناعات المتعلقة بالفضاء، وكذلك التقنيات والهندسة الطبية. وتعتبر أشعة الليزر CO2 النابضة واحدة من أهم طرق التصنيع المستقرة والمتسخدمة فى التطبيقات الصناعية. وتتأثر دقة الأجزاء المنتجة وجودة أصطحها بمتغيرات عملية التصنيع المختلفة بالإضافة الى كل من نوع وسمك الخامة التى يتم تصنيعها. وفى الدراسة الحالية تم تقييم بعض عناصر الجودة عند تصنيع ثقوب دقيقة متنوعة على شرائح من اللدائن سمكها ١ مم ، ٢ مم باستخدام أشعة الليزر CO2 النابضة. وقد تمت دراسة تأثير متغيرات عملية التصنيع شملت: قدرة مصدر أشعة الليزر، سرعة التشغيل، معدل التغذية وكثافة النبضات، على جودة الثقوب المنتجة، وذلك باستخدام أسلوب تصميم التجارب. وقد تم استخدام نظام للرؤية الألية لتقييم أبعاد وشكل الثقوب المنتجة والأخطاء التى ظهرت فيه. كما تم تطوير أربعة نماذج رياضية مبنية على النتائج المعملية لحساب و تقييم خصائص الجودة للثقوب المنتجة بناء على قيم متغيرات عملية التصنيع التى تم اختيارها فى الدراسة. ويتيح تطبيق هذه النماذج الفرضة لتحديد أنسب قيم لمجموعو عناصر التشغيل محل الدراسة والتى تمكننا من الحصول على مستوى الجودة المطلوب عند تصنيع الثقوب الدقيقة على شرائح من اللدائن سمكها ١ مم، ٢ مم باستخدام أشعة الليزر CO2 النابضة.

**Keywords:** Microdrilling, $CO_2$ laser, Quality aspects in laser micro machining

## 1. Introduction

Industry continuously strives to make products that are smaller and lighter, yet with increased functionality. Several methods are used to produce micro-machined devices with dimensions down to micro and nano levels. These methods include photolithography, etching techniques, diffusion of dopants, implantation, laser micro machining, and others [1]. The most commercially known types of industrial lasers are the Nd:YAG laser, CO2 laser and Excimer laser [2]. Laser hole drilling is historically the most common commercial application since lasers started extensively to be used in industry [3]. Over the past twenty years lasers have provided the microelectronics and automotive sectors in particular with an effective tool for producing high quality micro-holes.

The application and performance of lasers in machining is affected by factors such as the average power and power intensity, beam mode, beam polarization, wavelength ($\lambda$), focal spot size and depth of focus (DOF). In the case of CO2 pulsed laser, the most significant parameters that affect quality include average laser power, drilling speed, feed rate, and pulse intensity. The precision of the positioning system together with the type and thickness of the material to be machined are also very important factors that significantly affect quality of machined holes.

Hoffman and Miglior [4] reported that the dimensional accuracy of laser cut of carbon steel, stainless steel and aluminium can be held up to ± 130 μm and surface finish under 0.8 μm $R_a$ value. Shimizu et al. [5] studied the effects of laser power and speed on the process capability and reported that the dimensional accuracy for cutting 1.2 mm steel sheet was within ± 20 μm while the surface roughness was 5 μm (maximum peak to valley height). Nuss and Geiger [6] conducted a detailed laser cutting study on steel to understand the effect of beam polarization on precision. Osada [7] described an experimental study of ultra-fine cutting of steel plates by a CO2 laser. A shorter focal length lens and a smaller incoming beam diameter were found to be essential to obtain high precision in laser cutting. Dilthey et al. [8] demonstrated that the accuracy of laser cutting is improved if the laser beam has a Gaussian energy distribution. The above-mentioned studies deal with relatively thin plates (1-3 mm) that have kerf widths of the order of (0.02 mm). High accuracies could be achieved in these cases since the kerf is small, and the inaccuracy could be expected to grow with thicker plates.

The objective of the present study is to investigate the accuracy levels obtained when micro features are produced on non-metal (ACRYLIC) sheets 1 and 2 mm thick. The study considers the analysis of some quality aspects for circular holes processed using pulsed CO2 laser. Hole diameter, diameter deviation from nominal value, out of roundness of hole entrances, centre distance between holes, protrude error and the hole conicity were evaluated for the manufactured holes. Empirical models are developed to describe the relation between the observed inaccuracies and the selected machining parameters.

## 2. Experimental work

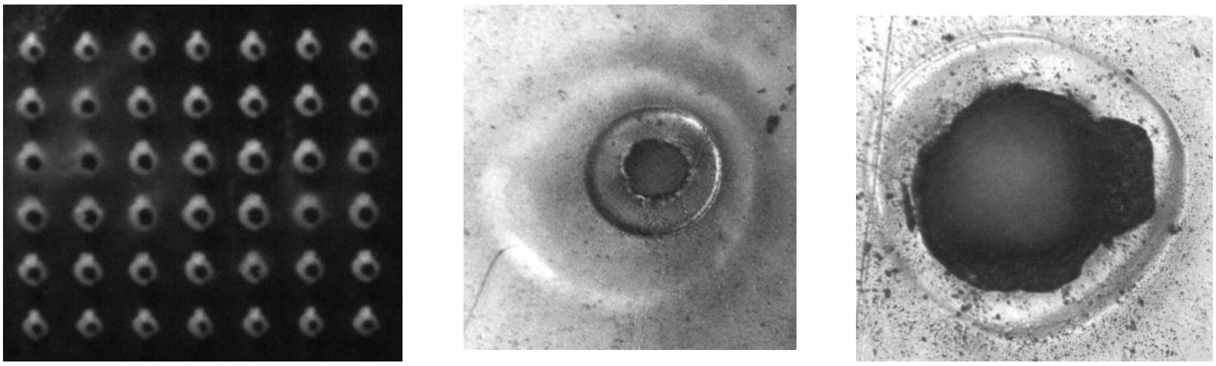
A CO2 pulsed laser machine (model X2-660 – Universal Laser Systems) was used in the experimental work. The machine has the following main characteristics; maximum operating power 100watt, 50mm focal length, feed rates ranging from 200×200 to 1000×1000 dpi, and pulse intensity 500 or 1000 ppi. To study the process capability of the machine and investigate the effect of different process parameters on the quality of produced parts a design of experiments approach was adopted. Fig. 1 shows a typical image of a part produced in single experimental run. The heat affected zone can be seen clearly on both faces of sheet material.

The sample comprises three sets of holes having nominal diameters of 140μm, 210μm and 280μm, respectively. Each sample contained 42 holes (3 sets, each 14 having the same nominal diameter). Experimental runs were performed to produce the sample part at different levels of the selected process parameters according to the design of experiment (DOE) proposed. The parameters considered in the study are the average power (P, watts), the speed (S, mt/sec), the feed rate (f, dpi), the pulse intensity (I, ppi), the material type, and thickness (T, mm). Table 1 gives the results of only twenty seven runs performed on sheets 1 mm thick, while keeping the values of power intensity constant at 500 ppi. A similar set of experimental runs were performed using the 2 mm thick sheets.

A vision-based approach was applied for the measurement of produced holes features. A calibrated CCD-Camera was used to capture a microscopic image of produced holes. An image processing package (IMAQ Vision Builder) was used for the analysis of captured images and evaluation of dimensional and geometrical errors. Fig. 2 shows the technique applied for the estimation of hole diameter and out of roundness using image analysis. The software package creates two concentric circles that encompass the hole profile. Radial rays originating from the center of the concentric circles will intersect the hole cross-section profile in a set of points ($x_i$, $y_j$). A least squares method was applied to estimate the diameter and center of the circle that best fits the points ($x_i,y_j$). The maximum deviation of the actual profile points from the corresponding fitted points is taken as the out of roundness for considered hole cross section. After estimating the diameters of the two hole entrances at both sides, the hole conicity is determined knowing the material thickness.

## 3. Results and discussion

(Ed, μm), out of roundness (Er, μm), hole conicity (Ch), and protrude error (Ep, μm). Each quality characteristic value shown in



(a) (b) (c)

Fig. 1. Typical images of micro-drilled holes, sample layout (a), lower sample surface (b) and upper sample surface (c).

Table 1
Average values of quality characteristics for holes produced in 1 mm thick ACRYLIC sheets at specified levels of selected process parameters

| Process parameters | | | Average deviation, μm | | | Ave. roundness error, μm | | | Ave. protrude, μm | | | Ave. conicity | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Power (Watt) | Speed (m/sec) | Feed (dpi) | 140 | 210 | 280 | 140 | 210 | 280 | 140 | 210 | 280 | 140 | 210 | 280 |
| 60 | 10 | 250 | 12 | 17 | 24 | 10 | 11 | 10 | 26 | 27 | 29 | 0.11 | 0.12 | 0.13 |
| | | 500 | 9 | 11 | 11 | 10 | 11 | 10 | 24 | 25 | 27 | 0.10 | 0.11 | 0.12 |
| | | 1000 | 6 | 5 | 8 | 10 | 10 | 10 | 23 | 24 | 26 | 0.10 | 0.11 | 0.12 |
| | 15 | 250 | 5 | 9 | 16 | 10 | 11 | 10 | 26 | 26 | 29 | 0.10 | 0.12 | 0.12 |
| | | 500 | 1 | 3 | -1 | 9 | 10 | 9 | 23 | 24 | 27 | 0.10 | 0.11 | 0.12 |
| | | 1000 | -7 | -8 | -6 | 8 | 9 | 9 | 23 | 23 | 26 | 0.10 | 0.11 | 0.12 |
| | 20 | 250 | -5 | -4 | 4 | 9 | 10 | 9 | 25 | 26 | 28 | 0.10 | 0.11 | 0.12 |
| | | 500 | -10 | -8 | -3 | 8 | 9 | 9 | 22 | 23 | 25 | 0.10 | 0.11 | 0.12 |
| | | 1000 | -16 | -21 | -20 | 8 | 8 | 8 | 22 | 23 | 25 | 0.10 | 0.11 | 0.12 |
| 80 | 10 | 250 | 34 | 29 | 35 | 13 | 12 | 11 | 28 | 27 | 29 | 0.12 | 0.13 | 0.13 |
| | | 500 | 22 | 19 | 26 | 11 | 11 | 11 | 27 | 27 | 28 | 0.12 | 0.13 | 0.13 |
| | | 1000 | 11 | 11 | 17 | 10 | 11 | 10 | 27 | 26 | 28 | 0.12 | 0.12 | 0.12 |
| | 15 | 250 | 17 | 19 | 21 | 11 | 11 | 10 | 27 | 26 | 29 | 0.12 | 0.12 | 0.13 |
| | | 500 | 10 | 17 | 13 | 10 | 11 | 10 | 27 | 26 | 28 | 0.12 | 0.12 | 0.12 |
| | | 1000 | 3 | 2 | 6 | 9 | 10 | 10 | 27 | 26 | 27 | 0.11 | 0.12 | 0.12 |
| | 20 | 250 | 2 | -2 | 15 | 9 | 10 | 10 | 25 | 26 | 28 | 0.11 | 0.12 | 0.13 |
| | | 500 | -4 | -4 | 0 | 9 | 10 | 9 | 24 | 25 | 27 | 0.11 | 0.12 | 0.12 |
| | | 1000 | -8 | -6 | -6 | 8 | 9 | 9 | 24 | 24 | 25 | 0.10 | 0.11 | 0.12 |
| 100 | 10 | 250 | 43 | 42 | 54 | 14 | 13 | 12 | 32 | 31 | 32 | 0.14 | 0.14 | 0.15 |
| | | 500 | 37 | 37 | 40 | 13 | 13 | 11 | 29 | 29 | 29 | 0.13 | 0.14 | 0.15 |
| | | 1000 | 19 | 22 | 32 | 11 | 11 | 11 | 28 | 28 | 29 | 0.13 | 0.14 | 0.15 |
| | 15 | 250 | 24 | 32 | 50 | 12 | 12 | 12 | 31 | 29 | 31 | 0.13 | 0.14 | 0.15 |
| | | 500 | 16 | 26 | 31 | 11 | 12 | 11 | 27 | 28 | 28 | 0.13 | 0.13 | 0.14 |
| | | 1000 | 10 | 9 | 13 | 10 | 11 | 10 | 27 | 27 | 28 | 0.13 | 0.13 | 0.14 |
| | 20 | 250 | 7 | 9 | 29 | 10 | 11 | 11 | 28 | 28 | 30 | 0.13 | 0.14 | 0.14 |
| | | 500 | 2 | 4 | 9 | 9 | 10 | 10 | 27 | 27 | 28 | 0.13 | 0.13 | 0.14 |
| | | 1000 | 1 | 3 | 3 | 9 | 10 | 9 | 25 | 26 | 27 | 0.12 | 0.13 | 0.14 |

table 1 is the average of 14 readings repeated at the same experimental run. The estimated hole diameters are not shown in table 1, instead their deviations from nominal values are given.

Multiple linear regression analysis was preformed to relate the change in the produced hole diameter with the corresponding process parameters. Eq. (1) give the three empirical models developed for the three nominal diameters considered in the study: 140 μm, 210 μm, and 280 μm respectively. The estimated coefficients of correlation was better than 0.9.

$$D_{L140} = 187 + (0.436P) - (2.47S) - (0.0144f) - (0.0191Pi) - (17.5T)$$
$$D_{L210} = 257 + (0.487P) - (2.52S) - (0.0179f) - (0.020Pi) - (17.1T). \quad (1)$$
$$D_{L140} = 327 + (0.598P) - (2.54S) - (0.0246f) - (0.0187Pi) - (17.0T)$$

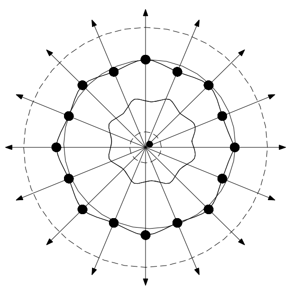
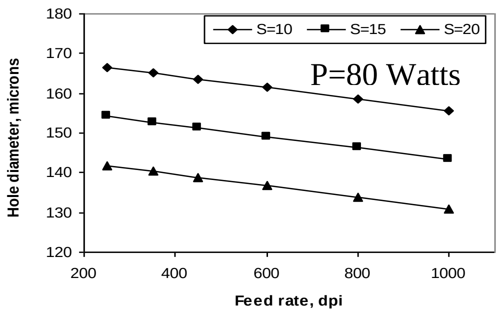


Fig. 2. Principle of hole diameter estimation using image analysis.

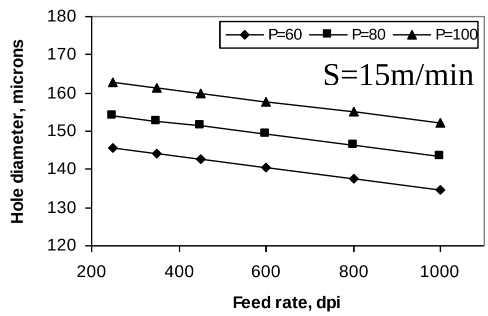
Where; $D_L$ is the hole diameter (μm), *P* power (watts), *S* speed (m./sec), *f* feed rate (*dpi*), *Pi* pulse intensity (*ppi*) and *T* material thickness (mm).

The model suggests that the produced hole diameter is directly proportional to the average power, and inversely proportional to each of the speed, feed, pulse intensity and material thickness. Based on eq. (1), fig. 3 shows the effect of change in feed rate on the diameter of the drilled holes (for 140 μm nominal diameter holes). In fig 3-a, the average laser power was kept constant at 80 Watts but in the fig. 3-b, the speed was kept constant at 15 m/min. It is obvious that, as the feed rate and speed increase, hole diameter decreases. This can be attributed to the decreased time of interaction between the laser beam and part material. On the other hand, the increase in average laser power results in a relative increase in produced hole diameter. This can be explained by the increased heat input, hence material removal associated with higher average power levels. Similar conclusions can be drawn for the other sets of holes (210 μm, and 280μ m diameters).

A general model, eq. (2), was also developed that can estimate the value of the produced hole for the three sets of the three considered diameters (*X*). A correlation coefficient of 0.9 was also considered in the analysis but the p-value is slightly less than the case shown in eq. (1).




(a)




(b)

Fig. 3. Effect of feed rate on drilled hole diameter at different speed values (average power=80 Watts), (a), and at different average laser power (speed =15 m/min), (b).

$$D_{LX} = (X+47) + (0.3 + X/1000)P) - (2.51\ S) -((X/1000)\ f)) - (0.019 + P_i)) - (17.2 +T). \quad (2)$$

Fig. 4 shows the correlation between the measured error in hole diameter and the corresponding estimated values using eq. (1), (for the twenty seven samples of 140 μm nominal diameter holes given in table 1). The figure indicates good correlation between measured and estimated error values and illustrates the effect of average laser power on value of deviation in hole diameter. Table 2 gives a comparison between maximum and minimum error values estimated using the developed general and individual models for the three sets of hole diameters.

Besides error in hole diameters, the out of roundness and hole conicity were evaluated. The average measured values of both quality characteristics are given also in table 1. The out of roundness was estimated based on a least squares analysis method. The values shown in table 1 indicate higher roundness errors for the smaller hole diameter (140 μm set). Eq. (3) are the regression models developed to relate roundness error to variations in the considered process parameters. The models indicate the pronounced effect of the average power, speed and material thickness on the roundness error. Both feed and pulse intensity have limited effect on roundness error.

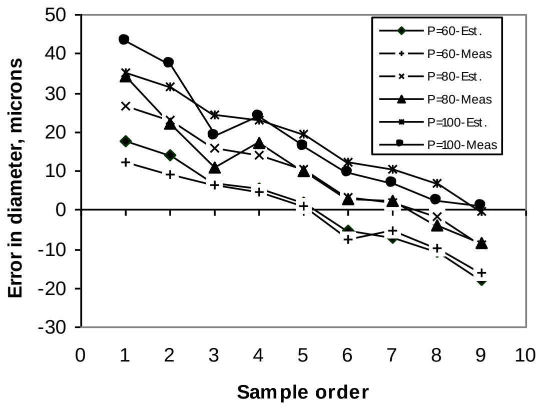



Fig. 4. Relation between estimated and measured values of deviation in the 140-μm-hole diameter at different average laser power.

$$E_{r140} = 13.0 + (0.0440P) - (0.250S) - (0.00160\ f) - (0.00193\ Pi) - (0.804T)$$
$$E_{r210} = 12.6 = (0.0346P) - (0.179S) - (0.00135f) - 0.00143\ Pi) - (0.500T) - (0.00129\ f) - (0.00096\ Pi) - (0.390T) - (0.00129\ f)\text{-}(0.00096\ Pi) - (0.390T). \quad (3)$$

Where: *Er* is the roundness error (μm)

Based on eq. (3), fig. 5 shows the effect of change in feed rate on the diameter of the drilled holes (for 140 μm nominal diameter holes). In fig. 5-a, the average laser power was kept constant at 80 Watts but in the fig. 5-b, the speed was kept constant at 15 m/min.

It is obvious from fig. 5 that the roundness error decreases by decreasing the average laser power and increasing both speed and feed rates of laser beam. This can be explained by the decreased material removal rates associated with lower average power, higher speed and feed rates which results in better surface and improved roundness of drilled holes. The correlation between measured roundness errors and their corresponding values estimated by eq. (1) is clear as illustrated in fig. 6 for the twenty seven samples of 140 μm nominal diameter holes given in table 1.

Another important quality characteristic of micro-drilled holes is the hole conicity. Hole conicity is the difference between the upper cross section diameter and lower cross section diameter of the hole divided by the sheet thickness. Eqs. (4) are empirical models, developed using experimental results, that describe the relation between conicity and variation in process parameters for the three sets of nominal hole diameters.

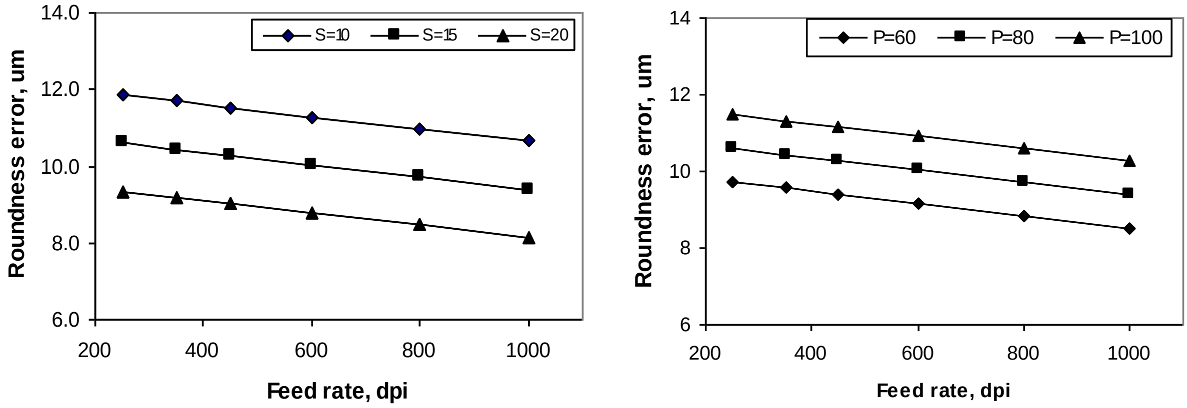
$$Ch_{140} = (148 + (0.722P) - (0.712S) - (0.008f) - (0.004Pi) - (73.9)T)/1000$$
$$Ch_{210} = (163 + (0.687P) - (0.674S) - (0.007f) - (0.005Pi) - (77.6)T)/1000$$
$$Ch_{280} = (175 + (0.605P) - (0.668S) - (0.005f) - (0.003Pi) - (78.5T))/1000\,. \quad (4)$$

Where *Ch* is the hole conicity.

Table2
Comparison of relative hole error of the measured hole values and corresponding values estimated using developed models

| Hole size | 140 μm holes | | 210 μm holes | | 280 μm holes | |
|---|---|---|---|---|---|---|
| | Min | Max | Min | Max | Min | Max |
| Individual model | -4.8% | +5.2% | -3.2% | +3.3% | -4.3% | +3.0% |
| General model | -4.9% | +5.8% | -3.0% | +4.2% | -5.3% | +1.8% |

Watts




(a) (b)

Fig. 5. Effect of feed rate on roundness of drilled holes at different speed values (average power=80 Watts), (a), and at different average laser power (speed =15 m/min), (b).

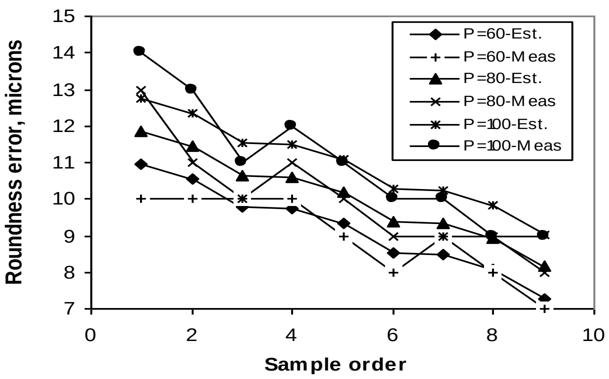



Fig. 6. Relation between estimated and measured values of roundness error in the 140-μm-hole diameter at different average laser power.

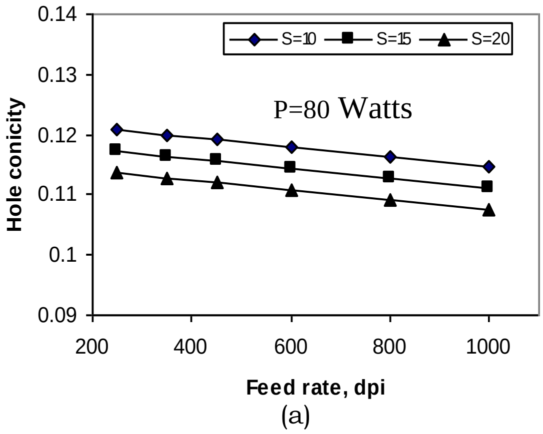
Eqs. (4) indicate that the concity error is directly proportional to average laser power and inversely proportional to the each of the speed, feed rate and the pulse intensity. Based on eq. (4), fig. 7 shows the effect of change in feed rate on the diameter of the drilled holes (for 140 μm nominal diameter holes). In fig. 7-a, the average laser power was kept constant at 80 Watts but in the fig. 7-b, the speed was kept constant at 15 m/min. An obvious effect of average laser power on hole conicity can be observed. It is also clear that as speed and feed rate increases the conicity error slightly decreases.

Fig. 8 shows a good correlation between the measured hole conicity errors and the corresponding estimated values using eq. (4), (for the twenty seven samples of 140 μm nominal diameter holes given in table 1).

A typical characteristic observed in the micro-drilled holes is the protrude on the upper surface of the sheet material as shown in the image of fig. 1-c. The radial protrude length, (Pe, μm) was estimated for the micro-dilled holes. Table 3 shows the maximum and minimum protrude length for the three hole sets.

## 4. Conclusions

This study presents the effect of different process parameters on the quality characteristics of microdrilled holes when a $CO_2$ pulsed laser is used to machine Acrylic sheets of 1 and 2 mm thickness. The study is based on



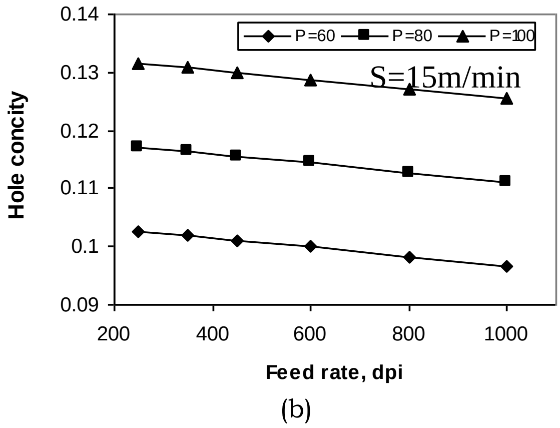




Fig. 7. Effect of feed rate on roundness of drilled holes at different speed values (average power=80 Watts), (a), and at different average laser power (speed =15 m/min), (b).

Table 3
Maximum and minimum protrude length for the three hole sets

| Hole set | 140 μm | | 210 μm | | 280 μm | |
|---|---|---|---|---|---|---|
| | Min | Max | Min | Max | Min | Max |
| Protrude length (μm) | 21.80 | 32.17 | 22.59 | 31.07 | 24.41 | 32.49 |

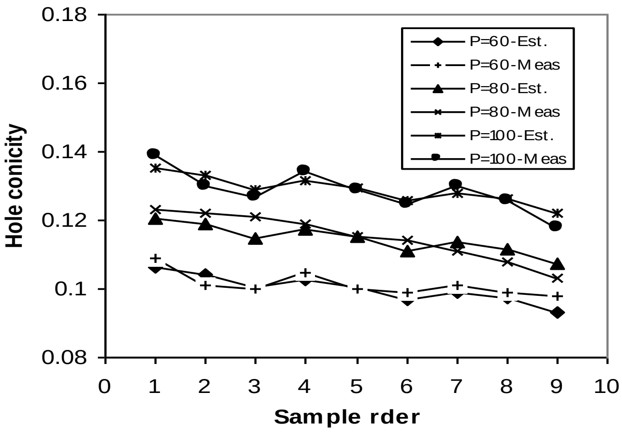



Fig. 8. Relation between estimated and measured values of conicity error in the 140-μm-hole diameter at different average laser power.

the results obtained from set designed experiments. A vision based technique was adopted to evaluate micro holes dimensions and geometrical characteristics. Results of the experimental work were used to develop empirical models which relate the considered quality characteristics to the change in the selected process parameters. Within the range of parameters considered in the study the following conclusions can be drawn.

As the average laser power increases, errors in both dimensional and geometrical features increase too.

An increase in the laser beam speed, feed rate, and pulse intensity results in a relative decrease in the errors in both dimensional and geometrical features of microdrilled holes.

The empirical models developed on the basis of experimental results show good correlation with measured values and can be used to optimize the selection of process parameters in order to get better quality of microdrilled holes on Acrylic sheets using CO2 pulsed laser.

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