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ORIGINAL ARTICLE

Dimensional analyses and surface quality of the laser cutting process for engineering plastics

Mustafa Kurt · Yusuf Kaynak · Eyup Bagci · Halil Demirer · Mahir Kurt

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Abstract In this study, the effect of the CO_2 laser cutting process parameters (gas pressure, cutting speed, and laser power) on the dimensional accuracy and measured surface roughness of engineering plastic (PTFE and POM) materials was investigated. Cutting surface profile of specimens was examined by using an optical microscope. The surface quality of specimens was examined by measuring surface roughness and form error. Analysis of variance (ANOVA) and regression analyses are employed to assess the effect of the process parameters on the dimensional accuracy.

Keywords Laser cutting · Analysis of variance (ANOVA) · Engineering plastics · Dimensional error

M. Kurt (✉) · Y. Kaynak
Faculty of Technical Education, Mechanical Department,
Marmara University,
34722 Istanbul, Turkey
e-mail: mkurt@marmara.edu.tr

E. Bagci
UME-National Metrology Institute of Turkey,
Dimensional Group Laboratories,
Kocaeli, Turkey

H. Demirer
Faculty of Technical Education,
Metallurgical and Materials Department, Marmara University,
Istanbul, Turkey

M. Kurt
Marmara University,
Institute For Graduate Studies In Pure and Applied Sciences,
Istanbul, Turkey

1 Introduction

Delrin (POM) is a highly versatile engineering plastic with metal-like properties. It offers an excellent balance of desirable properties that bridge the gap between metals and ordinary plastics. Since its introduction in 1960, it has been widely used around the world in many applications, such as in the automotive, appliance, construction, hardware, electronic, and consumer goods industries. Delrin has gained widespread recognition for its reliability and performance in thousands of engineering components. Industrial products made with Teflon (PTFE) have exceptional resistance to high temperatures, chemical reaction, corrosion, and stress-cracking. The properties of Teflon make it the preferred engineering plastic for a host of industrial applications and different processing techniques [1].

Laser cutting processes have been widely used in most manufacturing industries. Plastic, metallic and the other materials can be effectively cut, welded, and surface treated by this process. In comparison to other cutting processes, it has several advantages. It belongs to the most rapid cutting processes, the forces acting on a product during cutting being negligible; therefore, no particular clamping of the workpiece is required in cutting of even the thinnest of materials. In addition, the level of noise is particularly low. Cutting may proceed in different directions in a plane and in space, which enable efficient cutting-out and trimming of shaped parts. The laser cutting process is relatively easy to automate and it has good chances of adaptive control. Laser light may be used to cut almost all materials [2]. Additionally, the cost of laser technology is still extremely high, though it is constantly falling, and consequently its use is justified only if the quality of the end product is decisively better and if the process becomes more reliable. Laser applications in plastic material cutting have grown

Table 1 The process parameters and their levels for the dimensional geometry

Levels	Process parameters		
	(A) Pressure (bar)	(B) Cutting speed (mm/min)	(C) Power (W)
1	2.5	2	600
2	4.5	5	900
3	6.5	8	1,200

considerably in many industries since it is now possible to achieve a superior quality finished product along with greater process reliability [3].

The effects of CO_2 cutting parameters on the resulting cut quality for ceramics, sheet steel, and wood were investigated by several researchers [4–13]. Although, few of the researchers investigated the CO_2 laser cutting of plastics materials, the CO_2 laser cutting of POM and PTFE have not been studied yet.

Caiazzo et al. [3] presented the application of the CO_2 laser cutting process to three thermoplastic polymers in different thicknesses ranging from 2 to 10 mm. They examined laser power, cutting speed, gas pressure, and thickness as cutting parameters. Paulo Davim et al. [14] investigated cutting quality of PMMA by using CO_2 lasers. They presented some surface quality aspects of CO_2 laser cutting of linear and complex 2D. The effect of the process parameters (laser power and cutting velocity) on the quality of the cut for several polymeric materials was also investigated by Paulo Davim et al. [15]. Laser processing of plastics was also discussed by Brian Rooks [16]. Ilio et al. [17] investigated the laser cutting of aramid fibre reinforced plastics and presented a new methodology based on a digital image processing technique for evaluation of cut quality.

Keeping in view, the fundamental objective of this study is to understand the effect of the process parameters (gas pressure, cutting speed, and laser power) of laser cutting on the dimensional accuracy of engineering plastic (PTFE and POM) materials and measured surface roughness. A Nikon microscope was used to measure the form error and the surface defects of the produced parts.

Analysis of variance (ANOVA) and regression analyses are employed to find the optimal levels and to analyze the effect of the process parameters on the dimensional accuracy of engineering plastic materials.

Table 2 Cutting conditions

Number of test	Pressure (bar)	cutting speed (mm/min)	Power (W)
1	2.5	2	600
2	2.5	5	900
3	2.5	8	1,200
4	4.5	2	900
5	4.5	5	1,200
6	4.5	8	600
7	6.5	2	1,200
8	6.5	5	600
9	6.5	8	900

2 Experimental methods and measurements

This experiment was conducted on a TRUMPF L3030 CNC laser cutting machine. Process parameters (gas pressure, cutting speed, and laser power) and their level for the dimensional geometry is given in Table 1. The range of these variables was selected based on the manufacturer's recommendation, literature survey, and industrial applications. The settings of laser cutting parameters are given in Table 2.

In this study, PTFE and POM materials were cut using the CO_2 laser cutting method. These materials are extensively used in industry. The nominal dimensions of specimens are given in Fig. 1. These nominal dimensions were especially selected to use for our proposed areas. The main mechanical and thermal properties of PTFE and POM are given in Table 3.

2.1 The measurement of circular parts

The measurement of diameters of circular parts is of critical importance for many applications. One of the most important fundamental factors for engineering components is the precision assembly. Hence, in this study, diameter errors of specimens were measured using a coordinate measuring machine (5-axis coordinate measuring machine-Brown & Sharpe Global Status 9128 5PDEA CMM). The major system components are the 3-axis mechanical set-up, the probe head, the control unit, and the PC. The CMM used here is a vertical arm CMM, using a Renishaw PH sensor mount with a touch-trigger probe. The measured values of circular POM and PTFE specimens are given in Table 4. For POM, the maximum deviation from the nominal value is 0.67 mm. For PTFE, the maximum deviation from the nominal values is 0.78 mm.

2.2 The measurement of square parts

The dimensional error of square specimens was measured using Clemex software. The gage block was placed on the edges of the square parts and then the software was calibrated with respect to the gage block, and finally, the

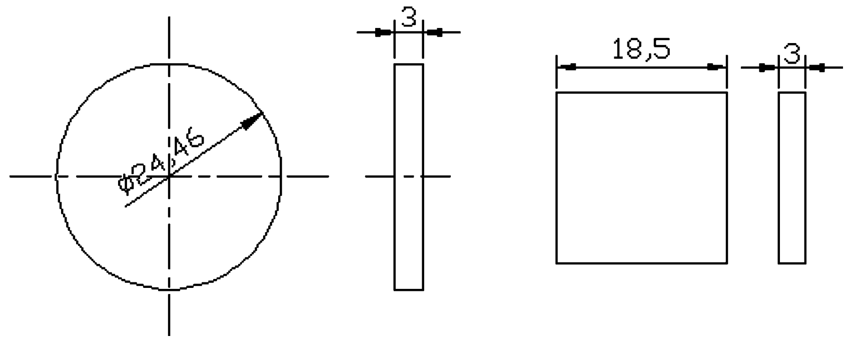


Fig. 1 The nominal dimensions of the specimens (dimensions are given in mm)

dimensional error of square specimens was measured. The measured values of square POM and PTFE specimens are given in Table 5. The maximum deviation of POM from the nominal value is 0.89 mm. The maximum deviation of PTFE from the nominal value is 1.2 mm.

2.3 Surface roughness measurements

One of the basic principles of modern manufacturing industry is the quality of manufactured parts. The quality of the manufactured parts depends on their geometries and surfaces textures such as roughness. It is well known that surface roughness effects fatigue life, corrosion, and friction and thermal conductivity of parts. In laser cutting, some factors such as gas pressure, cutting speed, and laser power can affect surface roughness of produced parts. In this study the selection of these parameters was conducted by previous experience, laser cutting handbooks, and trials. Initial trials were performed in order to better understand the effect of cutting parameters on desired surface quality of produced parts.

A few researchers have investigated the relationship between surface roughness and its relevant factors such as thickness, power, and cutting speed of the laser cutting process. They used polyethylene, polypropylene, and polycarbonate. Their experimental study illustrated that the value of surface roughness decreases as cutting speed increases [3].

The aim of this study is to understand the effect of cutting parameters (pressure, cutting speed, and laser power) and materials properties (POM and PTFE) on surface roughness. In this study, the surface roughness on the job is monitored by using a contact-type stylus (Mahr Perthometer Concept). All the measurements were repeated at least three times in order to obtain more accurate readings.

There are several ways to describe surface roughness. One of them is average roughness, which is often quoted as Ra symbol. Ra is defined as the arithmetic value of the departure of the profile from the centerline along sampling length as shown in Fig. 2. It can be expressed by the following mathematical relationships [18].

$$R_a = \frac{1}{L}\int_0^L |Y(x)|dx \tag{1}$$

where Ra is the arithmetic average deviation from the mean line; Y is the ordinate of the profile curve; L is the sampling length.

Table 3 Main mechanical and thermal properties of PTFE and POM [1]

Properties	PTFE	POM
Density (kg/m^3)	2,162	1,410
Compressive strength (MPa)	24.3	104
Tensile strength (MPa)	25	69
Elongation (%)	300	30
Coefficient of linear expansion (x10^{-5} in./in./F)	7.5	5.4
Thermal conductivity (W/m/C)	0.24514	0.22495
Specific heat (J/kg/C)	1,054	1,475
Melting temperature (C)	335	168

Table 4 Measured values of circular POM and PTFE specimens (dimensions are in mm)

Trial no.	POM	PTFE
1	23.96	23.68
2	23.94	23.73
3	23.79	23.80
4	24.02	23.90
5	23.93	23.73
6	23.83	23.75
7	24.00	23.77
8	23.93	23.81
9	23.81	23.70

Table 5 Measured dimensional values of square POM and PTFE specimens (dimensions are in mm)

Trial no.	POM	PTFE
1	17.73	17.44
2	17.77	17.50
3	17.73	17.43
4	17.86	17.64
5	17.62	17.30
6	17.68	17.40
7	17.76	17.48
8	17.87	17.68
9	17.61	17.30

2.4 The microscopic observations of cut surfaces

In the laser cutting of materials, observation of any material's cut edge produced by CO_2 laser and gas jet will reveal regular-spaced rippled or striation appearing on the side wall of the cut. The formation of striations has received much attention due to its effect on the quality of laser cutting. Fushimi et al. [19] investigated the formation of striations and concluded that formation of striations on the surface of cut occurs due to the cycle variations in driving factor of oxidation reactions. These reactions are related to the partial pressure of oxygen in the cutting area. They illustrated that striation frequency increases with an increase in cutting speed, yet not linearly. According to King et al. [20], there is a positive relationship between striation frequency and cutting speed in the laser cutting process, however, the study of Karebernick et al. showed that there is no positive correlation between striation frequency and increasing surface roughness of the cut surface [21]. In addition to these, Rajaram et al. [22] indicated that the low speed results in good surface roughness and low striation frequency at the cutting edges. In this work, the striation frequency was not measured. However, the frequency of striation was observed visually by using a Nikon optical microscope for each specimen as shown Fig. 5.

3 Statistical analysis

3.1 Regression analysis

The pressure, cutting speed, and power were considered as variables in the development of mathematical models for the dimensional error of square specimens. The correlation between CO_2 laser cutting factors (cutting speed, power, and pressure) and dimensional value of POM and PTFE specimens was obtained by multiple linear regressions. A linear polynomial model was developed to control whether the dimensional error data represents a fitness characteristic as below:

- For circular specimens

For POM and PTFE specimens;

$$\begin{aligned} &\textit{Diameter and } \dim \textit{ensional value } = x_0 \\ &+x_1 A + x_2 B + x_3 C + \ldots\ldots\ldots + (\varepsilon) \end{aligned} \tag{2}$$

where $x_{1,2,}$ and x_3 are estimates of the process parameters and ε is error. A standard commercial statistical software MINITAB was used to derive the models of the form:

$$\begin{aligned} \text{POM diameter} &= 24,2 + 0,00417\,\text{A} + 0,0022\,\text{B} \\ &- 0,000306\,C \qquad R^2 = 92,6\% \end{aligned} \tag{3}$$

For PTFE specimens;

$$\begin{aligned} \text{PTFE diameter} &= 23,7 + 0,00583\,\text{A} + 0,0222\,\text{B} \\ &-0,000056\,C \qquad R^2 = 81,9\% \end{aligned} \tag{4}$$

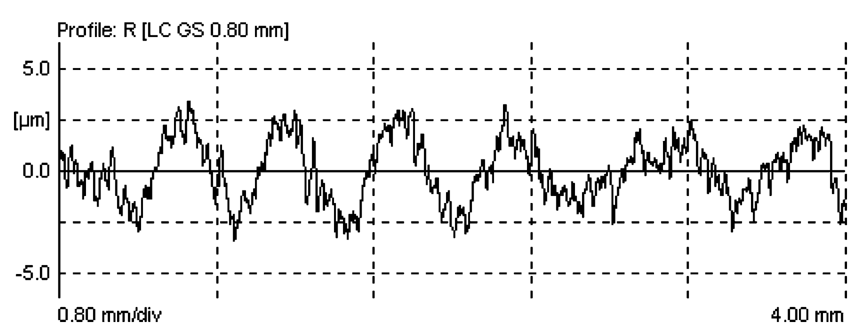


Fig. 2 A sample of measured surface roughness of the cut edges

Table 6 ANOVA results for values of circular POM specimens

Source of variation	Degree of freedom (DOF)	Sum of squares (S)	Variance (V)	F ratio (F)	P value (P)	Percent (%)
A	2	0.002822	0.002822	0.95	0.512	8.55%
B	2	0.018422	0.018422	6.23	0.251	55.78%
C	2	0.008822	0.008822	2.98	0.138	26.72%
Error	2	0.002956	0.002956			8.95%
Total	8	0.033022				100%

- For square specimens

For POM specimens;

$$\text{POM dimensional value} = 17,8 + 0,00042\,\text{A} + 0,0272\,\text{B} - 0,000183\,C \qquad R^2 = 89,3\% \tag{5}$$

For PTFE specimens;

$$\text{PTFE dimensional value} = 17,5 + 0,0078\,\text{A} + 0,0395\,\text{B} - 0,000243\,C \qquad R^2 = 84,1\% \tag{6}$$

In multiple linear regression analysis, R^2, which is called as R-sq, is the regression coefficient (R^2>0.80) for the models that indicates that the fit of the experimental data is satisfactory.

3.2 Analysis of variance (ANOVA)

ANOVA helps in formally testing the significance of all main factors and their interactions by comparing the mean square against an estimate of the experimental errors at specific confidence levels. These can be accomplished by separating the total variability of the S/N ratios, which is measured by the sum of the squared deviations from the total mean S/N ratio, into contributions by each of the design parameters and the error. First, the total sum of squared deviations SS_T from the total mean S/N ratio can be calculated as [23]:

$$SS_T = \sum_{i=1}^{n} (\eta_i - \eta_m)^2 \tag{7}$$

where n is the number of experiments in the orthogonal array and is the mean S/N ratio for the i th experiment.

The percentage contribution $_P$ can be calculated as:

$$P = \frac{SS_d}{SS_T} \tag{8}$$

where SS_d is the sum of squared deviations. ANOVA results are illustrated in Tables 6, 7, 8, and 9. Statistically, there is a tool called an *F*-test named after Fisher [24] to determine which design parameters have a significant effect on the quality characteristic.

4 Statistical and experimental results

4.1 Statistical results

For the diameter value of circular POM and PTFE specimens, the P-value reports the significance level (suitable and unsuitable) in Table 6. Percent (%) is defined as the significance rate of process parameters on diameter value. The percent numbers depicts that pressure (A), cutting speed (B) and power(C) have significant effects on the diameter value. It can be observed from Table 6 that A, B,

Table 7 ANOVA results for values of circular PTFE specimens

Source of variation	Degree of freedom (DOF)	Sum of squares (S)	Variance (V)	F ratio (F)	P value (P)	Percent (%)
A	2	0.003622	0.003622	1.23	0.449	9.29%
B	2	0.028156	0.028156	9.53	0.095	72.15%
C	2	0.004289	0.004289	1.45	0.408	10.99%
Error	2	0.002956	0.002956			7.57%
Total	8	0.039022				100%

Table 8 ANOVA results for dimensional values of square POM specimens

Source of variation	Degree of freedom (DOF)	Sum of squares (S)	Variance (V)	F ratio (F)	P value (P)	Percent (%)
A	2	0.001220	0.001220	0.25	0.802	1.87%
B	2	0.040066	0.040066	8.14	0.109	61.58%
C	2	0.018852	0.018852	3.83	0.207	29.88%
Error	8	0.004925	0.004925			6.67%
Total	2	0.065062				100%

and C affect the diameter value by 8.55, 55.78, and 26.72% in the laser cutting of POM specimen, respectively.

The gas pressure, cutting speed, and laser power factors presented statistical and physical significance on diameter value for cutting POM specimen as shown in Table 6.

It can be observed from Table 7 that A, B, and C affect diameter value by 9.29, 72.15, and 10.99% in the laser cutting of PTFE specimen, respectively. The gas pressure, cutting speed and laser power factors presented statistical and physical significance on diameter value for cutting PTFE specimens as shown in Table 7.

For dimensional value of the square POM and PTFE specimen, Table 8 shows that A, B, and C affect the diameter value by 1.87, 61.58, and 29.88% in the laser cutting of POM specimen, respectively. The gas pressure, cutting speed, and laser power factors presented statistical and physical significance on dimensional value for cutting POM specimen as shown in Table 8. Table 9 illustrates that A, B, and C influence diameter value by 1.96, 60.29, and 25.88% in the laser cutting of PTFE specimen, respectively.

The gas pressure, cutting speed, and laser power factors presented statistical and physical significance on dimensional value for cutting PTFE specimens as shown in Table 9.

Some significant results were obtained from the statistical study. The influence of cutting speed on diameter and dimensional values for cutting circular and square POM and PTFE specimens is important as shown in Tables 6, 7, 8, 9. As shown in the results of ANOVA, the laser power also significantly affects the diameter and dimensional values of produced circular and square POM and PTFE specimens. These two significant parameters must be regulated and optimized in order to obtain not only desired dimensions but also desired surface quality. Although these parameters importantly affect the quality of the produced parts, the degree of importance depends mainly on the properties and kind of the workpiece. Besides, the thickness of workpiece is also an effective parameter to obtain good cut surface in laser cutting process.

4.2 Experimental results

Determination of cut surface quality of produced parts can be best done by measurements of surface roughness. Figure 3 shows that surface roughness of PTFE decreases at higher cutting speeds and gas pressure. However, as the cutting speed increases (5 mm/min) together with the gas pressure (6.5 bar), surface roughness increase is insignificant. Figure 4 shows that measured surface roughness values of the cut surface of POM are similar to PTFE.

The best cutting speed for the best surface of cut was found to be 8 mm/min for the cutting of POM specimen. The tendency of process parameters such as gas pressure and cutting speed on roughness of cut surface is also approximate. Considering the literature, the influence of process parameters on surface roughness of cut surface of other polymers is not very different for the laser cutting of POM and PTFE specimens.

It can be concluded from Figs. 4 and 5 that striation frequency increases with cutting speed up to a specific speed (5 mm/min), after this, striation frequency starts to decrease and the quality of cut surface starts to deteriorate because of the low striation frequency. In order to obtain perfect quality of cut surface, the cutting speed should be optimized otherwise; the desired roughness value cannot be obtained from the surface of cut in the laser cutting process.

Table 9 ANOVA results for dimensional values of square PTFE specimens

Source of variation	Degree of freedom (DOF)	Sum of squares (S)	Variance (V) (F)	F ratio	P value (P)	Percent (%)
A	2	0.002743	0.002743	0.17	0.858	1.96%
B	2	0.084357	0.084357	5.08	0.164	60.29%
C	2	0.036220	0.036220	2.18	0.314	25.88%
Error	2	0.016595	0.016595			11.87%
Total	8	0.139914				100%

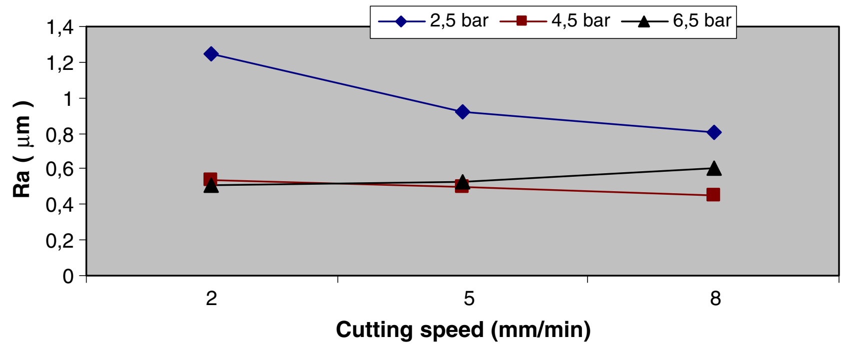


Fig. 3 Variation of Ra with respect to cutting speed for three different gas pressures and 900 W laser power cut in PTFE

Figure 5 shows a typical striation at the cut surface of specimen. In this study, the good surface quality obtained with low frequency of striation. Yet, the relationship between the cutting speed and roughness of cut surface is not linear.

In addition, some surface defects were observed on the cut surfaces of test 7 (6.5 bar gas pressure, 2 mm/min cutting speed, and 1,200 W laser power) due to the high gas pressure and high laser power (Fig. 6).

Some form error was also observed from the starting point of cut for circular parts (Fig. 8). These errors were measured by using a Nikon microscope and Optical Gaging Projector (Figs. 7 and 8).

It can be concluded that the value of form error depends on the gas pressure and laser power because form error value increases as gas pressure and laser power increases. The relationship among form error, gas pressure, and laser power is not linear.

5 Conclusions

In order to determine the influence of process parameters such as gas pressure, cutting speed, and laser power on dimensional, diameter and surface quality of engineering plastic under the CO_2 laser cutting process have been investigated experimentally and statistically. It should be referred that these practical results can be used in application of CO_2 laser cutting process. From this study, the following conclusions can be drawn:

- The cutting speed and laser power must be regulated and optimized in order to obtain not only the desired dimensions but also optimum surface quality and roughness values. The effect of gas pressure on desired dimensions can be negligible.
- Both POM and PTFE materials showed similar dimensional, diameter and surface quality errors tendency in spite of different materials properties. The good surface quality was obtained with low frequency of striation. Yet, the relationship between the cutting speed and roughness of cut surface is not linear.
- Cut surface defects are observed especially in the vicinity of the corner of square specimens. It was found that the reasons of occurrence of these defects can be high gas pressure and high laser power. The form error value increases as the gas pressure and laser power increases.

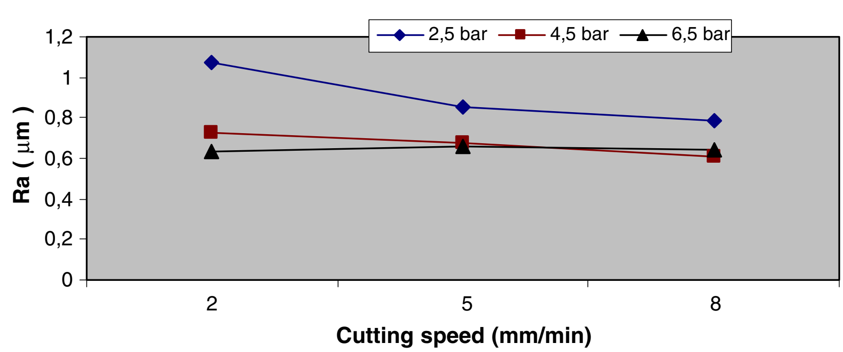


Fig. 4 Variation of Ra with respect to the cutting speed for three different gas pressures and 900 W laser power cut in POM

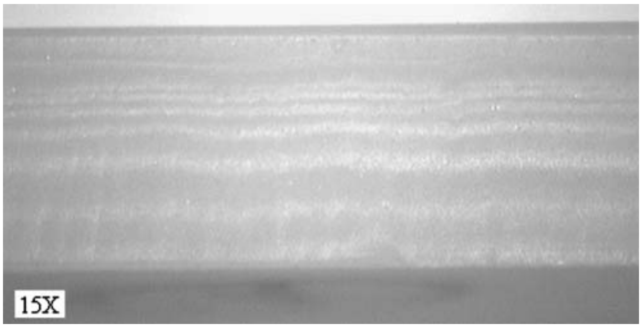


Fig. 5 A typical striation at the cut surface of the specimen

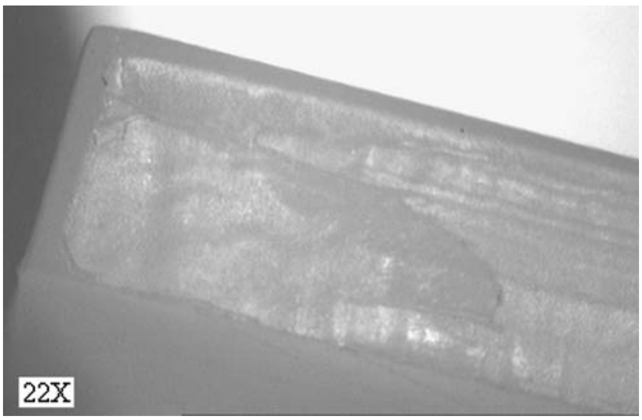
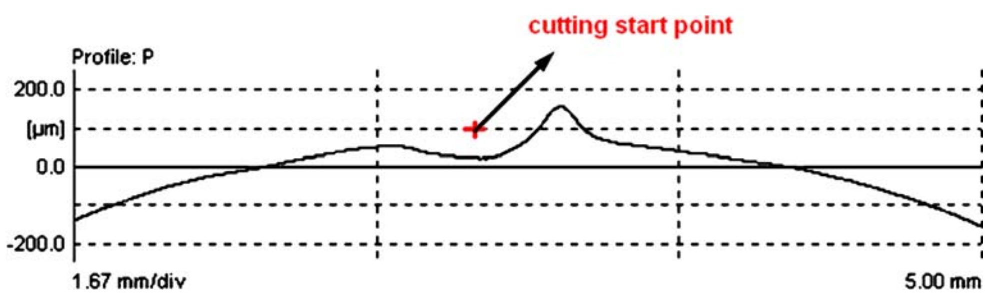


Fig. 6 Typical surface defects of a square specimen

Fig. 7 The form error of circular specimen



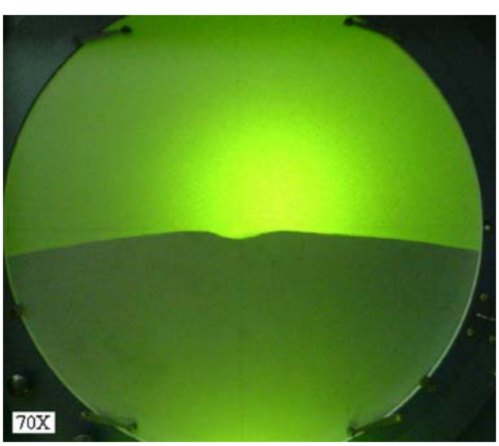


Fig. 8 Measurement of the form error of a typical circular specimen using the optical gaging projector

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