Scribing of ITO-coatings using a Q-switched Nd:YAG laser

S. C. Tam[a], Y. H. Chen[b], H. Y. Zheng[b], and W. L. Chen[c]

[a]School of Electrical & Electronic Engineering
Nanyang Technological University, Nanyang Avenue, Singapore 639798
[b]Gintic Institute of Manufacturing Technology
Nanyang Technological University, 71 Nanyang Drive, Singapore 638075
[c]Waterjet International Pte Ltd
202 Innovation Centre, NTU, Nanyang Avenue, Singapore 639798

ABSTRACT

This paper describes the results of optimising three process variables (control factors) to achieve a narrow line width in laser engraving of ITO conductive coatings using the Taguchi technique of experimental design. The laser used is a NEC Q-switched continuous wave (CW) Nd:YAG laser operating at a wavelength of 1.064 μm. The three process variables explored are: Q-switch frequency, speed of X-Y stage, and attenuator ratio of laser power. The various parameters were assigned to an L9 orthogonal array. The experiments were conducted with two repetitions each of which employs complete randomization. It was found that a narrow line width could be achieved with a Q-switch frequency of 25 kHz, scribing speed of 2000 mm/min, and beam attenuator setting of 35. A confirmation experiment of was carried out and the results fell within the predicted 95% confidence interval.

KEYWORDS: Nd:YAG laser, laser scribing, ITO-coating, Taguchi technique

1. INTRODUCTION

Processing of materials using lasers is a rapidly accepted technology in the new age where advances in laser technology have resulted in a better control of critical parameters of the laser system. However, the design parameters, which are set in the R&D phase and are often fixed by the laser suppliers, may no longer be applicable or optimal when there is a change of operating environment and a gradual deterioration of the laser components.

In any laser processing, such as laser scribing of ITO layers in order to attain a line width of 5-7 μm, the control parameters must be precisely selected. As there are generally no well-established mathematical models that can correlate the line width to the various control factors, an empirical method should be employed to explore the multi-dimensional parameter space. A statistical experimental design method such as Taguchi's method can be used to predict the effects of control factors on a desired response and the significance of these factors. Taguchi's method is reliable and generic, and can be applied to the performance optimisation of many types of laser processes.

2. EXPERIMENTAL SET-UP

In the laser scribing of ITO-coatings, the linewidth is one of the key quality parameters. It is mainly dependant on laser specifications (such as beam divergence angle, beam waist size, and laser power), beam delivery system (beam expander and focusing lens), and the interaction mechanism between the laser beam and the workpiece material. Our experiments were performed with an NEC M690B Q-switched Nd:YAG laser system. The Nd:YAG laser head can produce a maximum average laser power of 7 W at TEM_{00} mode with an acousto-optic Q-switch, whose pulse repetition rate can be adjusted from 1 kHz to 50 kHz in steps of 1 kHz.

Fig. 1 shows a block diagram of the laser processing system used in our study. The laser resonator consists of two plano-convex mirrors with radii of curvature of 0.8 m. The transmittance of the front mirror is 85%. The optical length is approximately 670 mm. The Nd:YAG rod is ϕ4×100 mm. An aperture with different diameters is placed inside the resonator to select laser beam modes. The laser beam is polarised by a Brewster plate in the Q-switch element. An attenuator is used to monitor the laser output power to 2 - 100% of the maximum. Then, a beam expander with an expansion ratio of 5× is used to reduce the beam divergence angle and to increase the beam diameter entering the ensuing optics. The focal length of the focal lens is 25 mm. A CCD camera and a TV monitor are used to observe the machining processes and to assist in the alignment of the beam to the workpiece.

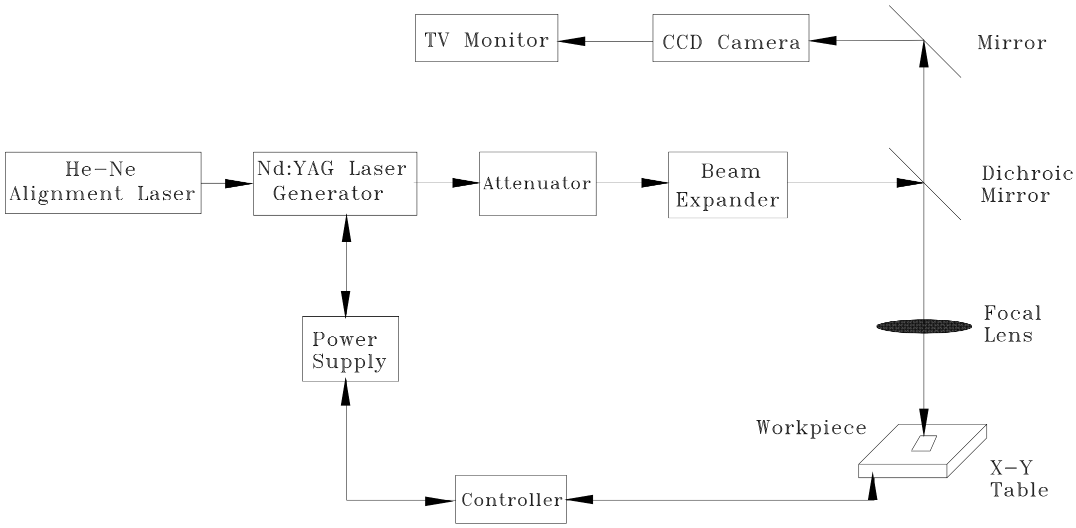


Fig. 1 Block diagram of laser processing system

For the system shown in Fig. 1, the focal spot size is given by[1]

$$d_0 = \frac{f\lambda}{T_1 \omega_0 \sqrt{1 + \left[\frac{l\lambda}{\pi\omega_0^2}\right]^2}} \tag{1}$$

where f is the focal length of the focusing lens, λ the laser wavelength, T_1 the beam expansion ratio of the beam expander, ω_0 the radius of the beam waist of the laser generator, and l the distance between the first lens of the beam expander and the beam waist. Theoretically, a short focal length and a large expansion ratio are needed to achieve a small spot size. However, the spot size is also affected by the optical performance (aberrations) of the focusing lens. The energy distribution within the focal spot determines the scribing width as the peak power and the interaction time have to exceed the threshold values before physical changes can occur.

The indium tin oxide (ITO) coated glass substrate is used in the manufacturing of liquid crystal displays (LCD). The ITO has a visible transmittance of over 90%, a thermal infrared reflectance of about 90%, a resistivity of approximately 10^{-4} Ω•cm, and a good adherence to many substrates[2]. It is used as a transparent electrode in LCD manufacturing. When an electrical field is applied via the ITO electrodes, the electrical field arranges the liquid crystal molecules with their long axis parallel to the field lines. This realignment will cause light to be blocked by a polariser placed on the surface of the glass substrate. Here the glass substrate is borosillicate glass. Fig. 2 shows a cross sectional view of the ITO-coated glass.

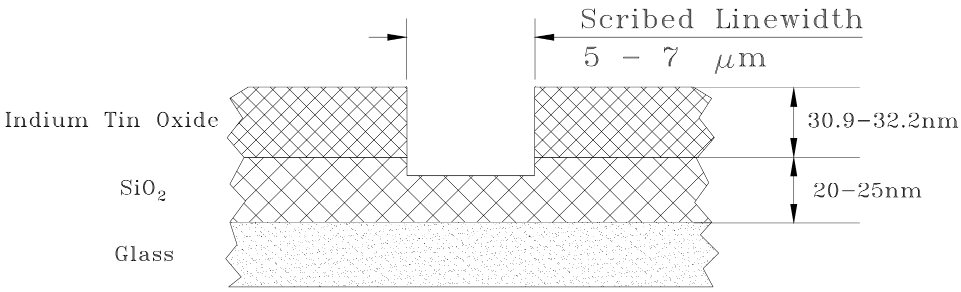


Fig. 2 Cross sectional view of the ITO coated glass showing the specifications for scribing

3. PRELIMINARY EXPERIMENTS

Understanding the role of a laser in a materials processing application requires a close look at the properties of both the laser beam and the material. The size and shape of the laser beam along with its power and energy will greatly affect the outcome of a process. Material properties such as reflectivity and thermal characteristics are also important[3]. Figure 3 shows the cause-and-effect diagram for line scribing. Clearly, the process is very complicated.

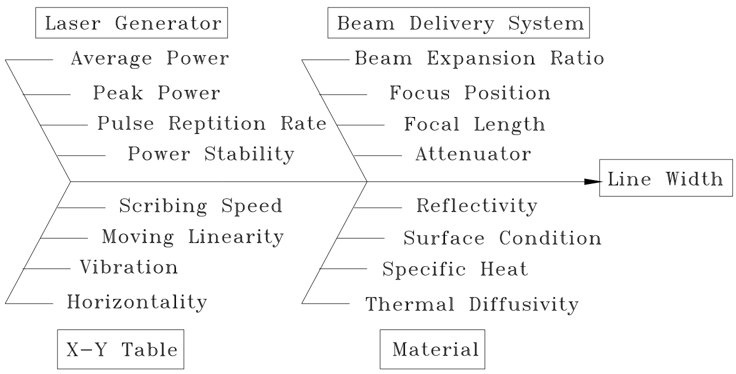
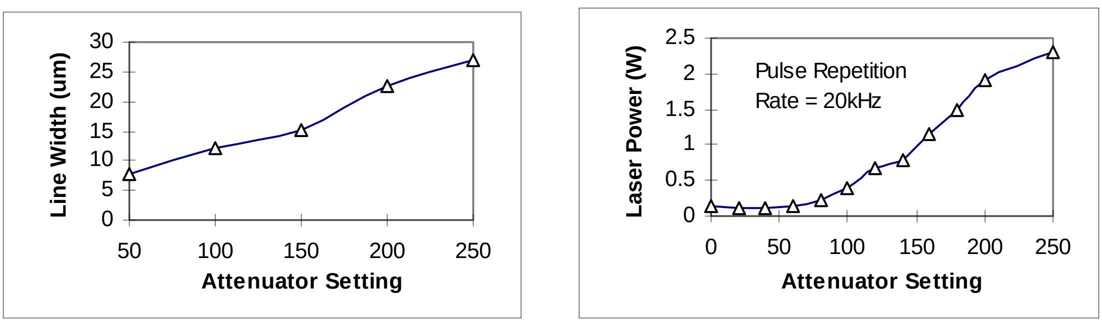


Fig. 3 Cause-and-effect diagram for line scribing

In order to obtain overlapping spots, the Q-switch frequency was fixed at 20 kHz. Speed of X-Y table was set at 2000 mm/min and the attenuator setting was varied from 50 to 250. The results are shown in Fig. 4. It is observed from Fig. 4(a) that the line width, averaged over two locations along the scribed line, increases as the laser power increases. As the required line width is specified to be around 5 to 7 μm, an attenuator settings of 50 and below should be used. Furthermore, it can be observed from Figure 4(b) that the relationship between the laser power and the attenuator setting is not linear. Note that attenuator setting ranges from 0 to 500.



(a) Line width vs. attenuator setting

(b) Laser power vs. attenuator setting

Fig. 4 Effect of changing the attenuator setting on line width and laser power

As mentioned before, the line width can also be affected by the speed of the specimen movement. In the experiments, the speeds were varied from 1000 mm/min to 5000 mm/min with the attenuator setting fixed at 50 and the Q-switch frequency fixed at 20 kHz. Figure 5 shows a plot of the relationship between specimen speeds and average line widths. It can be observed that the line width decreases marginally with increasing speed. It is because the absorbed energy by the specimen becomes lower when the table speed increases. However, the table speed should not be too high as the spots will not overlap enough to produce a continuous line.

The next exploratory experiment looked into the relationship between the Q-switch frequency (i.e. pulse repetition rate) and the line width. The Q-switch frequency was varied from 5 kHz to 30 kHz. The attenuator setting and the speed of the X-Y table were fixed at 50 and 2000 mm/min, respectively. The results are illustrated in Fig. 6. It is observed that, as the Q-switch frequency increases, the line width decreases. In fact, the peak power, the pulse width, and the average power are all affected by the Q-switch frequency, with the peak power bearing the largest effect. Hence, a Q-switch frequency of 15 kHz or above should be used.

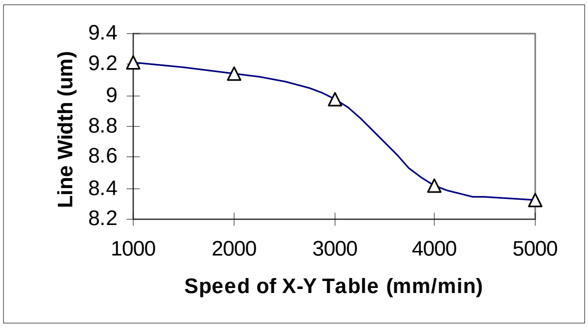


Fig. 5 Effect of specimen speed on line width

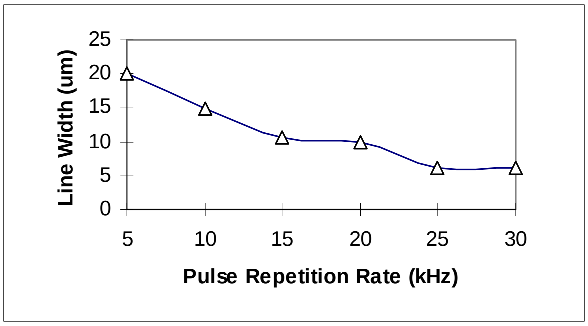


Fig. 6 Effect of pulse repetition rate on line width

Therefore, based on the preliminary experiments, the following ranges of process variables were chosen:

⇒ Q-switch frequency: 5 - 25 kHz
⇒ Table speed: 2000 - 4000 mm/min
⇒ Attenuator setting: 25 - 35

4. OPTIMIZATION USING TAGUCHI TECHNIQUE OF PARAMETER DESIGN

The Taguchi method of parameter design basically consists of the use of a family of fractional factorial experimental matrices that can be utilized flexibly. These matrices are called orthogonal arrays (OAs)[4]. The major steps of implementing the Taguchi method are: (1) identify the factors/interactions; (2) identify the levels of each factor; (3) select an appropriate OA; (4) assign the factors/interactions to columns of the OA; (5) conduct the experiments; (6) analyze the data and determine the optimal levels; and (7) conduct the confirmation experiment[5].

4.1 Experimental Layout

The factors to be studied are pulse repetition rate, table speed and attenuator setting (that affects the average laser power). Table 1 summarises the levels assigned to the various factors.

Table 1 Level Assignment for the Various Factors

Factor Symbol	Factor Name	Levels		
		1	2	3
Q	Q-switch Frequency (kHz)	15	20	25
S	Table Speed (mm/min)	2000	3000	4000
A	Attenuator Setting	25	30	35

An L9 orthogonal array was employed as it could provide the minimum number of degree of freedom required for the experiment. The column assignment and the experimental layout are shown in Table 2. Each experimental trial was performed with two repetitions. Complete randomization was utilized for the entire experiment.

Table 2 Experimental Layout Using an L9 Orthogonal Array

Trial No.	Factors[a]			Factor Names			Line Width[b] (µm)	
	Q[1]	S[2]	A[3]	Q-switch Freq. (kHz)	Speed (mm/min)	Attenuator Setting	Replicate #1	Replicate #2
1	1	1	1	15	2000	25	*	*
2	1	2	2	15	3000	30	*	*
3	1	3	3	15	4000	35	*	*
4	2	1	2	20	2000	30	*	*
5	2	2	3	20	3000	35	*	*
6	2	3	1	20	4000	25	*	*
7	3	1	3	25	2000	35	*	*
8	3	2	1	25	3000	25	*	*
9	3	3	2	25	4000	30	*	*

(a) superscript for factor represents column number, with column 4 unassigned.
(b) * represents the average linewidth determined from a specimen.

4.2 Raw Data and S/N Ratios

The results of the orthogonal experiment with two repetitions are shown in Table 3. The corresponding S/N ratios are also indicated in the table. The response, in this case the line width, was a "nominal-the-best" quality characteristic. Therefore, the S/N ratios were computed using Equation (2). It can be observed that the S/N ratios are merit functions that take into account of both response average and response variability. The larger the S/N ratio, the lower the linewidth, variability is, hence better quality.

$$S/N = +10\,log\left(\frac{V_m - V_e}{rV_e}\right) \tag{2}$$

where r is the number of tests in a trial (number of repetitions regardless of noise level), V_m is the variance due to mean , and V_e is the variance due to error[4]. V_m and V_e are calculated by

$$V_m = \frac{1}{r}\left[\sum_{i=1}^{r} y_i\right]^2 \quad \text{and} \quad V_e = \frac{1}{r-1}\left[\sum_{i=1}^{r}(y_i - \bar{y})^2\right] \tag{3}$$

where y_i is the value of response for the i-th test and $\bar{y}$ is the average response under that treatment combination.

4.3 Data Analysis

The common practice in analyzing data for nominal-is-best characteristics is to perform analysis on S/N ratios (to identify factors that affect the variability significantly), followed by analysis of variance (to identify factors that affect the mean significantly).

Table 3 Raw Data and S/N Ratios			
Trial No.	Line Width (μm)		S/N Ratio (dB)
	#1	#2	
1	11.32	12.51	23.01
2	10.54	11.08	29.04
3	9.24	11.73	15.44
4	9.85	10.32	29.64
5	5.62	8.14	11.59
6	9.42	8.23	20.39
7	6.48	6.46	53.21
8	7.95	9.81	16.54
9	7.69	8.43	23.74

4.3.1 Analysis of S/N Ratios

From the response graphs of the S/N ratios plotted, as depicted in Figure 7, the factors that are most significant for reducing variation could be identified. Since higher signal-to-noise ratio means greater robustness and smaller variability, it could be observed that the combined settings of Q_3, S_1 and A_2 would give the highest yield of S/N values.

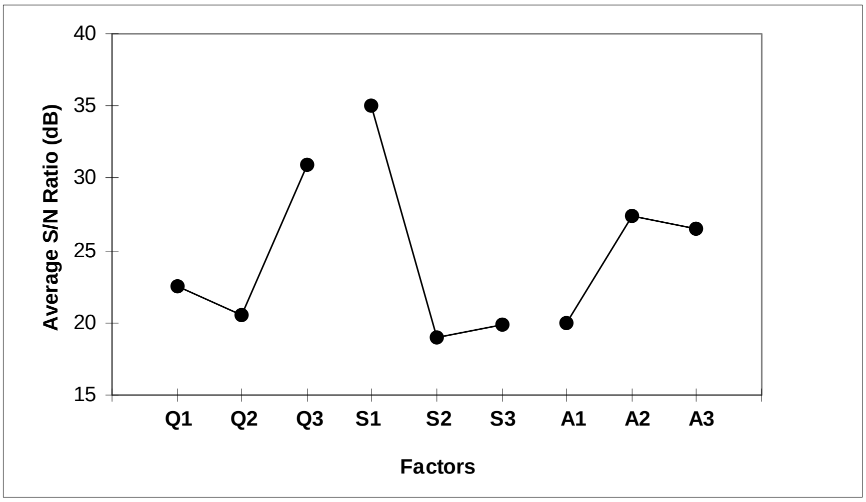


Fig. 7 Response graphs for the average S/N ratios

4.3.2 Analysis of Variance (ANOVA)

The technique of ANOVA was used to establish the significance of individual factors in affecting the variation of a desired response. The calculations were manually done and verified with the aid of ANOVA-TM 2.20 software distributed by Advanced Systems and Design Inc.[6].

Table 4 shows the results of ANOVA for the raw data after the "pooling up" strategy had been performed. *Df* is the number of degrees of freedom, SS is the sum-of-squares, *V* is the mean-squares or estimated variance, *F* is the variance ratio, *SS′* is the corrected sum-of-squares, ρ is the percentage contribution, "error1" corresponds to the total effect of the unassigned columns, "error2" is repetition error, and "epooled" represents the pooled estimate of experimental error.

Table 4 ANOVA Table - Raw Data							
Source	**Pool**	***Df***	***SS***	***V***	***F***	***SS′***	**ρ (%)**
Q	[N]	2	34.84	17.41	14.83	32.49	51.18
S	[Y]	2	1.21	0.61			
A	[N]	2	13.36	6.68	6.59	11.01	17.35
Error1	[Y]	2	4.11	2.05			
Error2	[Y]	9	9.95	1.11			
Epooled		13	15.28	1.175		19.97	31.47
Total		**17**	**63.47**				**100.00**

ANOVA of the raw data indicated that the effects of Q-switch frequency (Q) and attenuator setting (A) were highly significant in affecting the mean of the desired response. The effect of the scribing speed (S) was not significant within the range of parameter tested.

From the response graphs of the average raw data plotted against the three process variables as depicted in Figure 8, the combined parameter settings of Q_3, S_2 and A_3 would shift the mean to the desired target response.

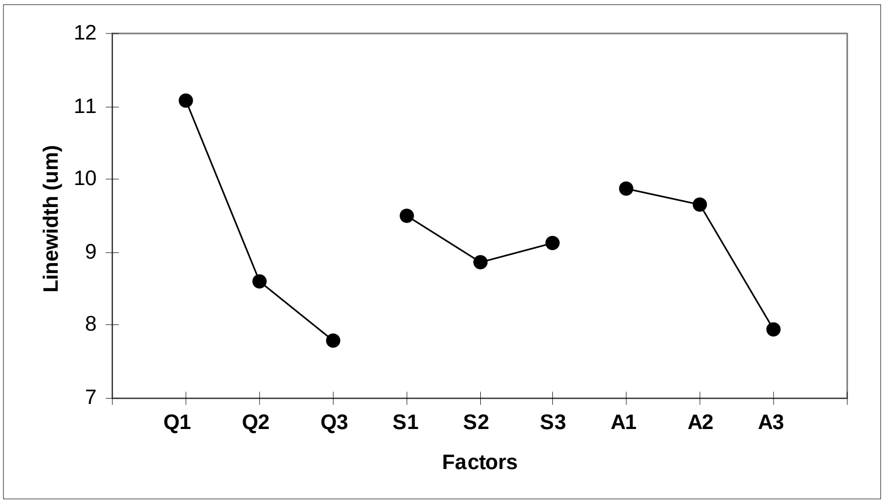


Fig. 8 Response graphs for the average raw data

4.4 Recommendations

Referring to the two graphs (Figure 7 and Figure 8), it could be observed that factor Q at level 3 produced a mean response closer to the target value and was least affected by variation. Therefore, this level was selected as the optimised level. Although level 2 of factor S shifted the mean response closer to the target value, level 1 was however chosen as it produced a response which was more robust. Furthermore, the difference in raw data between level 1 and level 2 of factor S was marginal. Because the difference between the variations produced by level 2 and level 3 of factor A is very small from Fig. 7 and the resulting mean response of level 3 of factor A is closer to the target value, the level of factor A was chosen to be 3 .

Based on the above analysis, the recommended parameter settings was therefore chosen to be Q_3, S_1 and A_3. In this experiment, the recommended parameter settings was part of the trials tested in the experiment. There are instances that the recommended combined settings may not be part of the trials, therefore suggesting the possibility that Taguchi technique of orthogonal array is able to identify the optimum parameters in the multi-dimensional parameter space.

The expected average at the optimum settings could be estimated from

$$\hat{\mu}_{Q_3A_3} = \overline{Q_3} + \overline{A}_3 - \overline{T} \quad (4)$$

where $\overline{Q_3}$ is the average response when Q is set at level 3, $\overline{A}_3$ is the average response when A is set at level 3 and $\overline{T}$ is the average of all the responses.

By substitution,

$$\hat{\mu}_{Q_3A_3} = \overline{Q_3} + \overline{A}_3 - \overline{T}$$

= 7.803 + 7.9450 - 9.1567
= 6.591 μm

The average response was calculated to be 6.591 μm.

The 95% confidence interval (*CI*) for the expected results from the confirmation experiment is:

$$CI = \sqrt{F_{\alpha,1,v_e} V_e \left(\frac{1}{n_{eff}} + \frac{1}{r} \right)} \tag{5}$$

where $F_{\alpha,1,v_e}$ is the F ratio at a significance level of α%, v_e is the degrees of freedom for the pooled sources of error, V_e is the error mean squares, n_{eff} is the effective total number of tests and r is the number of confirmation tests.

$$n_{eff} = \frac{Total\ number\ of\ observations}{1 + \left[Total\ degree\ of\ freedom\ associated\ with\ items\ used\ in\ estimating\ \hat{\mu}\right]} \tag{6}$$

By substituting the following: $F_{0.05,1,13}$ = 4.67; V_e = 1.175; $n_{eff} = \frac{18}{1+4}$ =3.6; r = 10, *CI* is calculated to be 1.44 μm. Therefore the 95% confidence interval should be given by

$$5.15\mu m \le \hat{\mu}_{Q_3A_3} \le 8.03\mu m \tag{7}$$

4.5 Confirmation Experiment

A confirmation experiment was conducted by performing five trials with two repetitions at the recommended combined settings of $Q_3S_1A_3$. It was found that the average raw data (dB), 19.21 dB, obtained from the confirmation experiment fell within the predicted 95% confidence interval. Table 5 illustrates the results and Fig. 9 shows the appearance of a scribed line.

Table 5 Confirmation Results

Trial No.	**Line widths (μm)**		**S/N ratios (dB)**
	#1	#2	
1	5.68	6.67	18.82
2	6.53	5.76	18.78
3	6.46	6.74	19.40
4	6.67	6.88	19.63
5	6.74	6.67	19.54
Average	**6.48**		**19.21**

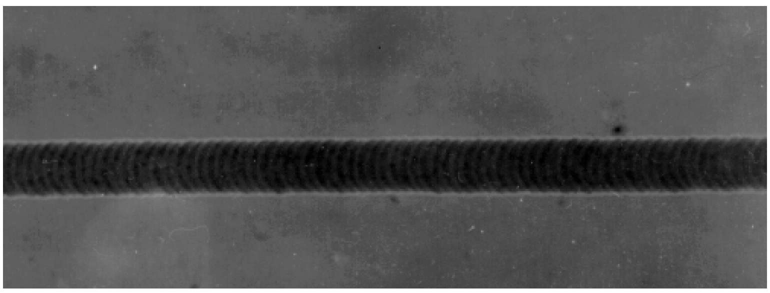


Fig. 9 Appearance of a scribed line

5. CONCLUSIONS

Using the Taguchi technique, the factors significantly affecting the variation in line width were identified. From the analysis of variance (ANOVA) of the raw data, the factors found significant were Q-switch frequency and laser output power. The speed of X-Y table was shown to be of little significance. The recommended settings were Q-switch frequency of 25 kHz, speed of 2000 mm/min and attenuator setting of 35. A confirmation experiment was conducted and the average line width of 6.48 μm, fell within the 95% confidence interval predicted by the Taguchi method. As for factors that affect the variability, measured by the S/N ratios, it was found that the Q-switch frequency and the attenuator setting were significant.

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