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Assessment of thermally induced shear stress and its effect on pattern waviness in CO_2 laser ablation of birefringent polymers

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Abstract

This article presents the application of custom-designed poledioscope for dynamic measurement of thermally induced shear stress, as a technique for monitoring waviness of the microscale patterns created using CO_2 laser, directly over optically birefringent polymers. Laser ablation experiments were conducted for three optical grade polymers: ethylene vinyl acetate, poly methyl methacrylate, and *allyl* diglycol carbonate under varying laser power and scanning speeds. A poledioscope, customized by incorporating beam splitter in place of rotating analyzer section of conventional polariscope, was used to assess the thermally induced shear stress on the materials in real time. The waviness of the profile of groove patterns was measured using a profilometer. The shear stress mapping and the profile waviness data recorded for range of laser processing parameters were further analyzed to determine that high thermally induced shear stress results in significant damage on waviness of the lased profile.

Keywords

Laser, poledioscope, shear stress, waviness, photoelasticity

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Introduction

In optical systems development, owing to its exceptional capability to generate precise features on optical materials ranging from soft polymers to hard metals, laser machining is one of the most widely used precision manufacturing techniques. Over years, while processing accuracy has improved significantly, during the processing of such optical grade materials, considerable wavy profiles get generated.[1,2] Unfortunately, in optical systems, waviness in machined profiles lead to undesirable results such as abrupt variations in refractive index, diffraction-induced scattering and spherical aberrations which render the lased surface unsuitable for the desired application. While, current laser control systems offer better control over laser power, scanning speed, scanning resolution etc., selection of optimized laser processing condition is material specific. Further, laser ablation models are material-dependent and are affected by microstructural integrity, phase transition mechanisms and fracture strength of the material, which are difficult to be assessed in real time.[3–5] With rapidly growing demand for precision manufacturing of optical microparts, application of high-frequency laser irradiation systems is widely evidenced in the literature. However, processing a range of materials using these laser systems is still stochastic in nature. As the published studies on surface quality enhancement in laser cutting are material specific,[6, 7] it becomes essential to establish a generic approach to asses the processing conditions dynamically in order to monitor the surface waviness and the damage occurred over the lased profile. In this article, authors have proposed a novel method of dynamic measurement of thermally induced shear stress, which is related to the waviness of the patterns generated. The authors have modified the polariscope (an instrument exclusively used for experimental stress analysis)

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by replacing a rotating analyzer section with a beam splitter to acquire birefringent images for different orientations.

Few researchers have proposed methodologies for enhancement of surface integrity in laser machining.[8–10] These include using complex mathematical models, statistical interpretation techniques by parameter variations and experimental nondestructive techniques. While all of these methods have application specific advantages, they all conclude that the surface quality is affected by thermal parameters in the machining process. Thermal parameters in laser machining lead to thermal stress in the material undergoing lasing. Thus, relating the dynamic thermal stress during lasing to the surface integrity aids in monitoring the same. Evaluation of thermal stresses in laser machining has been facilitated mathematically [11] and experimentally using photoelasticity. [12] However, in these papers, the authors have focused on residual thermal stresses in laser ablation and hence thermal stress in real time during laser ablation process was not reported.

Experimental study

Materials and methods

In this article, the authors have related the thermally induced shear stress in real time (during laser cutting process) using photoelasticity to the surface waviness generated in laser machining in order to monitor the generated waviness. A custom-designed poledioscope integrated with laser was used to assess the time varying thermally induced shear stress. Photoelastic method was implemented to assess thermally induced shear stress in real time. Finally, a profilometer was used to assess the profile waviness. The waviness was related to real-time thermal stresses. Three different materials namely ethylene vinyl acetate (EVA), poly methyl methacrylate (PMMA) and *allyl* diglycol carbonate (CR-39) were used to demonstrate the feasibility of the proposed technique. These materials were selected for the experiments as they are the most common materials used in designing optical coatings, lenses, and optical guides, etc. which undergo laser cutting.[13–15] Details of these materials are listed in Table 1.

Poledioscope design configuration

The lasing process was performed on EVA, PMMA and CR-39 sheets of thickness 2.1 mm using CO_2 laser, and a custom-designed poledioscope was used to record the values of shear stress dynamically. A poledioscope is a modified polariscope (an instrument exclusively used for experimental stress analysis). Instead of a rotating analyzer section, a beam splitter is used to procure birefringent images for different orientations.[16] The poledioscope works on the principle of birefringence. Birefringence is defined as the property of certain materials such as calcite, glass, plastics and sapphire to show double indices of refraction when stress is induced in the material.[17] Polarized light falling on such stress-induced birefringent material shows different phase retardations in different directions. By evaluating the phase shifts incurred by the light beam which is refracted via the material on which stress is imposed, it is possible to extract the shear stress map of the material. This is done by using the phase shift data procured experimentally, combined with a set of mathematical equations. Figure 1 shows the schematic representation of poledioscope design configuration used in this experimental study.

Experimental method

The laser system manufactured by Universal Laser (VLS 2.30) which was used for this experiment is a

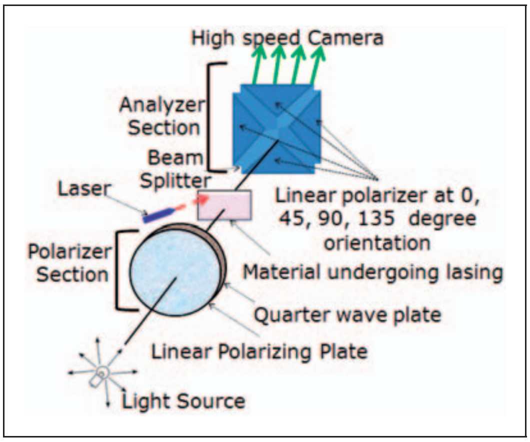

Figure 1. Schematic representation of poledioscope design configuration used for dynamic shear stress evaluation.

Table 1. Details of materials used in the experiment.

Sl. no.	Material	Supplier and grade	Applications
1	EVA	Westlake Chemical Corporation/EF437 Optical Grade	Photovoltaic coatings and transparent protective coatings
2	PMMA	Both Harvest Technology Company Limited and Optical grade	Optical guides and other optical ancillaries
3	CR-39	Optical Polymers International	Plastic eye glasses and low cost laboratory lenses

EVA: ethylene vinyl acetate; PMMA: poly methyl methacrylate; CR-39: allyl diglycol carbonate.

flat bed laser. A flat bed laser is used for material cutting/engraving in two dimensions. The maximum laser power for this laser is 30 W. The polarizer section of the poledioscope (shown in Figure 1) was placed on the flat bed, in such a way that the light beam emerging out strikes the sample undergoing laser cutting. Furthermore, to prevent the exposure of laser beam on the polarizer section, it was sealed with borosilicate glass; else the setup would have been damaged. The sample for lasing was placed above the polarizer followed by the analyzer section. Casio EXILIM ZS-200 camera was used in high speed movie mode at 1000 fps (frames per second) to capture the images in the analyzer section.

Capturing images under dynamic lasing operation

At each instant of lasing process, images were captured continuously in real time in sets of four. Each set signifies the birefringence induced in the material under lasing at a particular instant of time. At each instant, these four sets of images were fed to a program generated in the MATLAB software, developed using the mathematical equations stated in reference papers.[18,19] The program generated a shear stress map at a particular instant of time at the point and in the vicinity where lasing action was in progress. By acquiring sets of images in continuous manner and superimposing the stress maps, it was possible to obtain the full shear stress map of the sample being lased under dynamic operation. The images obtained at time $t = 2$ s during lasing EVA and the process to evaluate shear stress map are depicted in Figure 2. Similar experimental process was conducted for PMMA and CR-39.

Lasing under varying laser power and speeds

Laser engravings were generated on the EVA, PMMA, and CR-39 sheets under varying laser power and speeds. The method similar to section '*Capturing images under dynamic lasing operation*' was employed to capture and process images under dynamic conditions. Nine different combinations of power and speed were employed for each material to have a clear insight on the nature of stresses generated during lasing operation. The laser machine used for this experimental study allows the user to set the laser power and scanning speed in terms of percentages of maximum rated specifications, for example, maximum laser power is 30 W, so 11.5% of 30 = 3.45 W. For the laser scanning speed, the rated specification is not available in original manufacturer's specifications; for the purpose of quantification laser scanning speed was set for 100% and it was found that it takes 10 s to engrave over a length of 300 mm. From this it has been approximated that laser scanning at maximum speed is 1800 mm/min. Accordingly, in Table 2 process variables used for the nine experiments for each polymers are stated both in percentages (as set in the system dialog box) and the equivalent parameters in their units are approximated inside the brackets. For every experiment, a complete stress map was reconstructed using the images acquired by poledioscope setup as shown above.

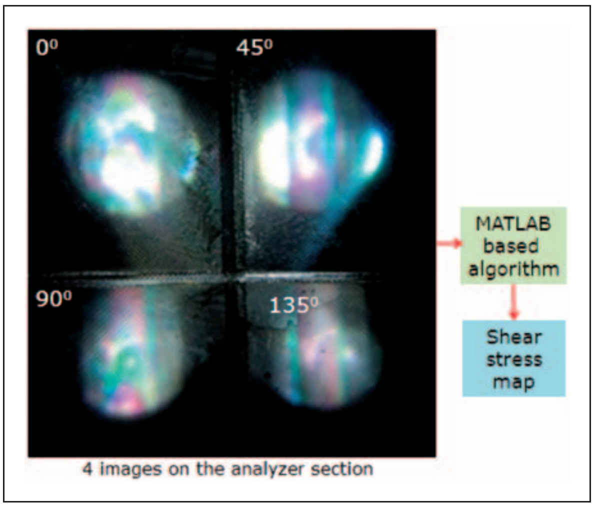

Figure 2. Four images obtained from analyzer section showing induced birefringence due to thermal stress.

Evaluation of surface waviness of the lased sample

In order to evaluate the waviness of the surface, the primary profile of the lased materials were captured using a profilometer. MarSurf XR 20 profilometer (manufactured by Mahr Company, Germany) was used for this purpose. The profilometer used is a stylus-based contact type instrument. The stylus traverses over the required sample to be examined and the profile so obtained is known as primary profile (P-profile). Extraction of waviness profile from primary profile is performed by filtering the primary profile. The Gaussian filter is most widely used in today's industrial applications. ISO: 11562 depicts that the waviness profile (W-profile) is extracted from the primary profile by filtering the P-profile with a low-pass Gaussian filter with cut-off wavelength λ_c followed by high-pass Gaussian filtering with cut-off wavelength λ_f. λ_c is the cut-off wavelength for the Gaussian filter defined by DIN EN ISO 4288, ASME B46.1.[20] The value of λ_f is not defined by ISO standards. Hence current industrial measurement systems ignore the step of high-pass Gaussian filtering with cut-off wavelength λ_f. Instead, the primary profile is first filtered using a low-pass Gaussian filter with cut-off wavelength λ_c. In this filtering process, one sample of the profile each from beginning to end is lost. The profile so obtained is then partitioned into adjacent segments. The number of such segments used is user-dependent, called calculation number (CN). The length of each segment of the profile would be equal

Table 2. Laser process variables (for experiments the values were set in percentage of maximum equipment rating).

Parameters	Unit	1	2	3	4	5	6	7	8	9
Laser Power	%	11.5	32.5	70.4	11.5	32.5	70.4	11.5	32.5	70.4
	Watt	(3.45)	(9.75)	(21.12)	(3.45)	(9.75)	(21.12)	(3.45)	(9.75)	(21.12)
Scan Speed	%	91	91	91	61	61	61	41	41	41
	mm/min	(1638)	(1638)	(1638)	(1098)	(1098)	(1098)	(738)	(738)	(738)

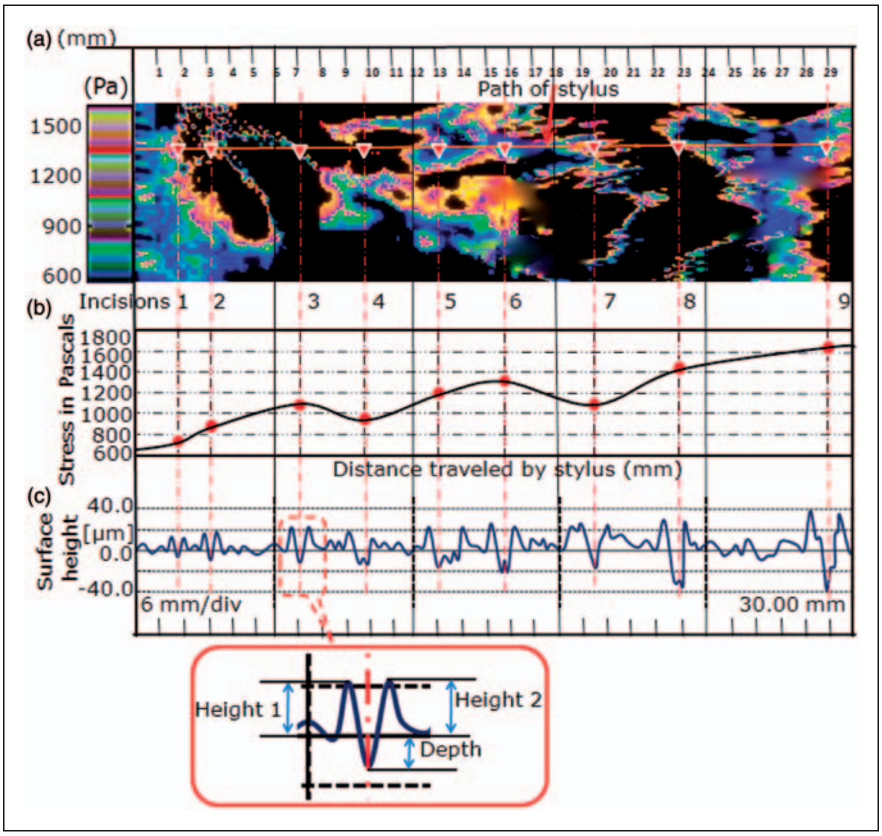

Figure 3. (a) Reconstructed shear stress map for EVA sample, (b) shear stress magnitude at the intersection of stylus and lased point and (c) waviness (W) profile of lased EVA.
EVA: ethylene vinyl acetate.

except the last one in some cases. In those cases, the last segment is discarded and the obtained profile is called W-profile.

From the above paragraph it can be well understood that waviness is not a standardized parameter. In order to eliminate this difficulty and maintain a proper industrial standard, MarWin software compatible with MarSurf machine was used to obtain the W-profile. CN used for waviness calculation in our experiment was set to 5.

Figure 3 shows the dynamically generated stress map, the stresses at the points of intersection of path of stylus and laser engravings and the waviness profile obtained for EVA material. The waviness profile at each engraving houses an engraving depth and two protrusion heights (Height 1 and Height 2), adjacent to the engraving depth. These protrusions contribute to the waviness of the patterned profile, which eventually leads to inaccuracies in fabricated optical parts.

Results

Figure 3 illustrates the shear stress map and the corresponding waviness of the lased profile at specific incision points. These points are identified by the user during experiments and the corresponding thermally induced shear stresses were computed. The profile waviness error measured by the three parameters (Height 1, Depth, and Height 2) as depicted in previous section, corresponding to the incision points are plotted in Figure 4. For all the three materials,

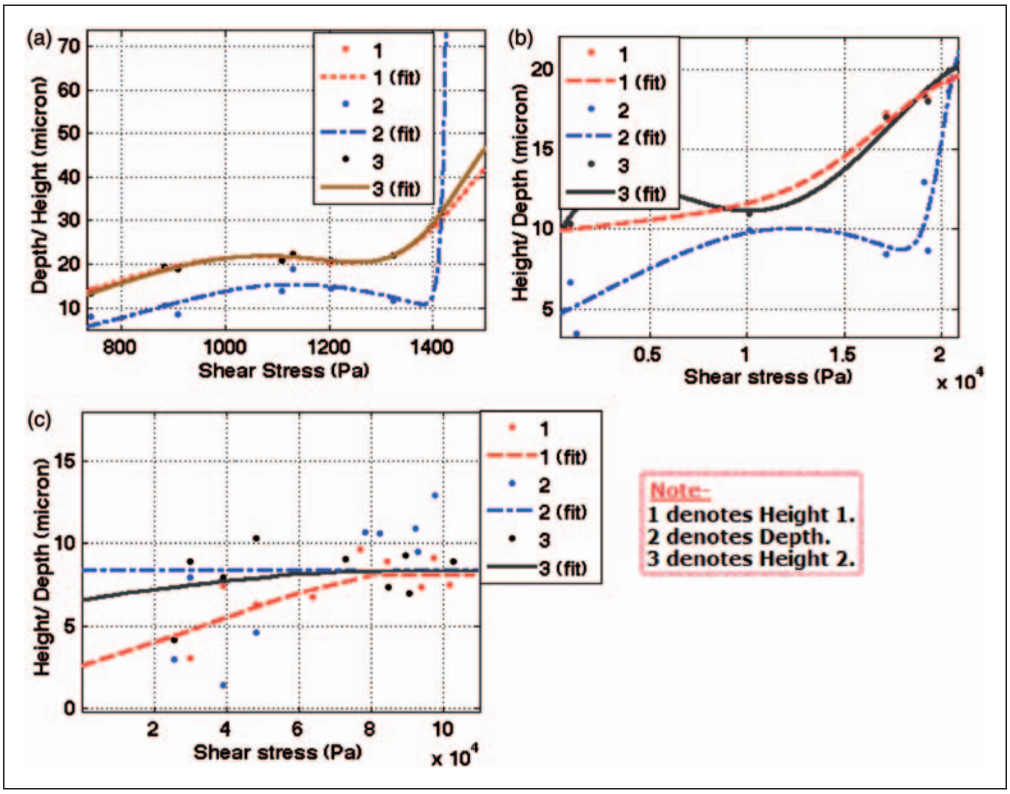

Figure 4. Height/Depth vs. shear stress (a) EVA, (b) PMMA and (c) CR-39 (height and depth conventions are as in Figure 3). EVA: ethylene vinyl acetate; PMMA: poly methyl methacrylate; CR-39: ally diglycol carbonate.

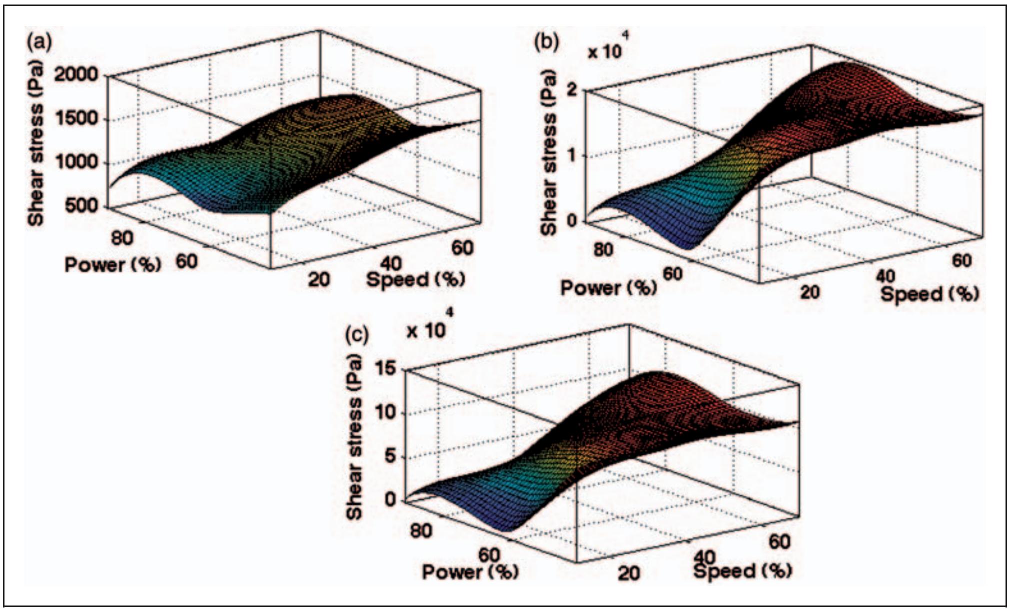

Figure 5. Surface plots for variation of shear stress with power and speed (a) EVA (b) PMMA (c) CR-39. EVA: ethylene vinyl acetate; PMMA: poly methyl methacrylate; CR-39: ally diglycol carbonate.

the relationships between the induced stresses during the processing and surface waviness generated are analyzed.

Further, the influence of laser power and scanning speed over thermally induced shear stress for the three work materials EVA, PMMA and CR-39 are plotted in Figure 5.

Following points can be inferred from the obtained experimental results:

- From Figure 4 it can be observed that the maximum induced shear stress in CR-39 was 66.9 and 13.3 times higher than that of PMMA and EVA, respectively. This effect is due to the higher melting temperature of CR-39 (338.7°C) as compared to PMMA (162°C) and EVA (76.1°C) as per the manufacturer's specifications. For laser ablation, CR-39 absorbs more thermal energy that leads to higher thermally induced shear stress.

- From Figure 4, it is observed that the increase in dynamic shear stress leads to an increase in waviness in the machined profile for all materials machined. For EVA and PMMA, it is seen that after a threshold value of induced shear stress (1320.43 Pa for EVA and 1.12×10^4 Pa for PMMA) the protrusion height rises very rapidly. Thus, by choosing the operating conditions within this threshold zone, profile waviness can be considerably monitored. Such threshold is not observed in CR-39.
- From Figure 5, it is seen that increase in laser power and decrease in speed results in increase in waviness of profile for all of the experimental materials. Higher lasing time and power results in material flow in its vicinity, which in turn results in waviness after solidification. This is due to melting followed by evaporation mechanism in laser machining.[21]

Conclusions

The custom-designed poledioscope has been successfully used to measure thermally induced shear stress under the influence of laser irradiation over birefringet polymers. The measured shear stress recorded at specified incision points and the corresponding profile surface errors measured by three parameters (Height 1, Depth, and Height 2) establishes clear understanding on their dependence. From the experimental study the following important results are noted:

- The images captured at 1000 fps measured by linear polarizer in four sets at 0°, 45°, 90°, and 135° and online processing demonstrated in this article facilitates dynamic shear stress mapping at any of the time-dependent points over lased profile. This dynamic assessment would enable dynamic process control of laser processing system, which is yet to be realized in commercial systems.
- Like in metals, birefringent polymers having higher melting point absorb more laser energy resulting in an increase in thermally induced shear stress and waviness.
- This has been noted from the results that maintaining shear stress around its threshold values by suitably selecting laser power and scanning speed assures the desired waviness as required for optical parts.

In summary, this case study demonstrates the potential of dynamic assessment of thermally induced shear stress using simplified poledioscope as a novel method to monitor the profile waviness. User can readjust the laser processing parameters based on the change in values of shear stress so as to maintain the desired surface integrity of the machined surface. From the industrial point of view, the proposed method has added advantages due to the fact that the method is nondestructive in nature. Further, most of the optical materials being birefringent in nature add to the feasibility of extension of this method to other optical materials.

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Conflict of interest

None declared.

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