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INTERACTION OF LASER RADIATION WITH MATTER. LASER PLASMA

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Control of laser machining of polycrystalline diamond plates by the method of low-coherence optical interferometry

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Abstract. **The possibility of applying low-coherence fibre optics interferometry for local contactless measurement of the optical thickness of polycrystalline diamond plates during high-power laser-pulse processing of their rough surface is demonstrated. A unique automated experimental system is developed to control the thickness of samples during ablation of their surface by a scanning 248-nm KrF excimer laser beam. It is shown that this technique is suitable for on-line control of laser polishing and for preparing plane-parallel plates.**

Keywords: *polycrystalline diamond plates, laser polishing of surfaces, low-coherence interferometry, ablation.*

1. Introduction

Due to the development of techniques for deposition of materials from gaseous phase in recent years, it has become possible to obtain polycrystalline artificial diamond plates, films and coatings whose size is large enough for fabricating various physical devices on their basis. Under such circumstances, the development of laser techniques for modification of diamond surfaces ensuring a high precision and speed of local processing (see, for example, [1]) becomes quite important. Moreover, being contactless, such a technique allows the use of interference technologies to control the shape and relief of the sample surface in real time.

We study in this paper the problem of controlling the thickness of diamond plates during polishing of their surface by laser beam ablation [2]. Polycrystalline diamond plates are usually quite rough, their roughness increasing with the sample thickness. For example, the roughness of samples having a thickness ~ 1 mm may exceed 100 μm. Contactless measurement of the profile of such objects using traditional interferometry is fraught with certain problems due to a number of reasons. The most important among these is that upon irradiation of a surface with a roughness considerably exceeding the wavelength of the probing radiation, the observed interference pattern is characterised by a developed speckle structure. Because of the speckle noise, it becomes practically impossible to reconstruct correctly the phase distribution of the interfering waves.

In order to eliminate the speckle noise, the probing radiation beam is focused in such a way that its diameter is smaller than the size of the surface inhomogeneities. In this case, a regular interference pattern is observed. However, during scanning of the sample surface by a probing beam, the continuity of its interference phase measurement is lost upon a transition from one nonuniformity of the relief to another if the difference in thicknesses of two adjacent surface regions exceeds half-wavelength of the probing radiation.

Since the application of coherent interferometry involves the measurement of the increment of plate thickness rather than the thickness itself, one incorrect measurement renders all subsequently measured values incorrect. The situation is further complicated due to a high degree of absorption of light in the graphitised surface layer, which is always formed during laser ablation of diamond [2, 3].

In this work, we describe the results of low-coherence fibre optics interferometry measurements of the thickness of polycrystalline plates of artificial diamond during ablation of their surface by a repetitively pulsed KrF excimer laser. Such measurements made it possible to eliminate the above-mentioned problems.

2. Experimental

A 248-nm excimer KrF laser (EMG 1003i, Lambda Physik) was used for microprocessing of the surface of diamond plates (Fig. 1). The laser pulse energy was 200 mJ for a pulse repetition rate up to 50 Hz and a pulse duration of 20 ns. To maximise the effect of so-called surface smoothing, the sample was irradiated at an angle of 70° to the normal [2]. The excimer laser beam was focused on the surface being processed as a spot of size 200×200 μm. The diamond plate was displaced using a controlled laser bench with a minimum step of 1 μm. The experimental setup ensured a simultaneous control of the sample displacement and its irradiation by the required number of laser pulses.

The diamond plates used in our experiments were prepared by gaseous phase deposition in a microwave plasma reactor [4] (model ASTeX-PDS19, power 5 kW, frequency 2.45 GHz). The optically transparent samples had

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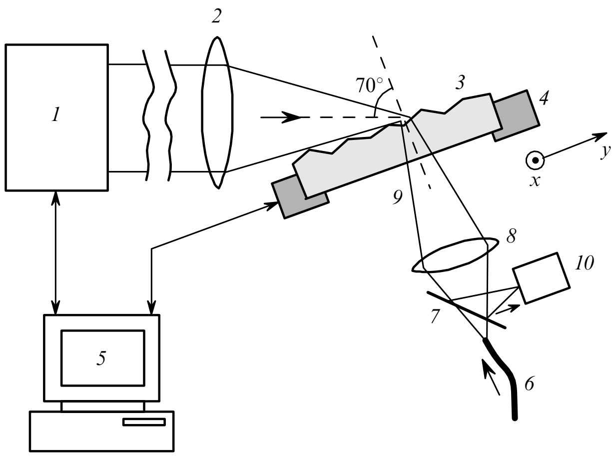


Figure 1. Experimental setup for controlled laser processing of diamond plates: (*1*) KrF excimer laser; (*2*) objective; (*3*) diamond plate; (*4*) $X-Y$ table; (*5*) controlling computer system for laser processing; (*6*) optical fibre from measuring block in the thickness control system; (*7*) 50 % beamsplitter; (*8*) objective; (*9*) probing beam; (*10*) photodetector.

a thickness of $150-200$ μm with a roughness of the unprocessed growth surface up to 30 μm. The other face of the samples was flat and had an optical quality.

The local control of thickness of diamond plates was carried out by low-coherence fibre optics interferometry (Fig. 2). Broadband radiation from source (*1*) with a coherence length equal to several wavelengths was directed at the surface of the sample through tunable interferometer (*2*). To eliminate the effect of the laser-induced opaque graphite layer on the observed interference signals, the sample was illuminated at right angles with the smooth unprocessed surface facing the radiation (see Fig. 1). The probe laser beam was focused on the surface being processed as a spot of size $20-30$ μm, which was smaller than, or of the order of, the characteristic transverse size of surface roughness (the size of individual diamond crystallites). The intensity of radiation reflected at the diamond plate surface was registered by single-element photodetector (*7*) (see Fig. 2).

The technique used by us for measuring the thickness of a transparent object was based on the fact that interference (i.e., summation of electric field strengths) for partially coherent light beams occurs only in the case when the optical path difference between these beams does not exceed a certain value called the coherence length of the radiation source. Otherwise, a simple summation of the beam intensities takes place. The plate thickness is measured as follows. Light from source (*1*) is split in the tuneable interferometer (*2*) into two beams with an optical path difference equal to $2x$, where x is the difference in the lengths of the interferometer arms. As a result of reflection from the sample, each of these beams is split once again into two parts so that four light beams arrive at photodetector (*7*). The trains (wave packets) of these beams are shown in Fig. 2. Their total optical path lengths are described by the expressions

$$l_1 = L,\ l_2 = L + 2x,\ l_3 = L + 2nd,\ l_4 = L + 2x + 2nd, \quad (1)$$

where d is the geometrical thickness of the sample; n is its refractive index; L is the total optical path from the tuneable interferometer to the front face of the sample and from the sample to the photodetector. In the optical scheme described above, interference will be observed only between those of the four beams whose trains overlap at least partially. Since the optical thickness of the sample exceeds the coherence length of the source, the interference pattern may be formed at photodetector (*7*) either by overlapping of wave trains 1 and 2 for a difference $|x| \leqslant l_{\text{coh}}/2$ ('zeroth' interference signal in Fig. 3) between the interferometer arms, or by overlapping of wave trains 2 and 3 for an interferometer arms difference $|x \pm nd| \leqslant l_{\text{coh}}/2$ (lateral signals in Fig. 3). Thus, the measurement of optical thickness nd of the sample is reduced to scanning of the difference between the arms of tuneable interferometer (*2*) and to the measurement of the distance between the central interference peaks of 'zeroth' order and one of the lateral signals in Fig. 3.

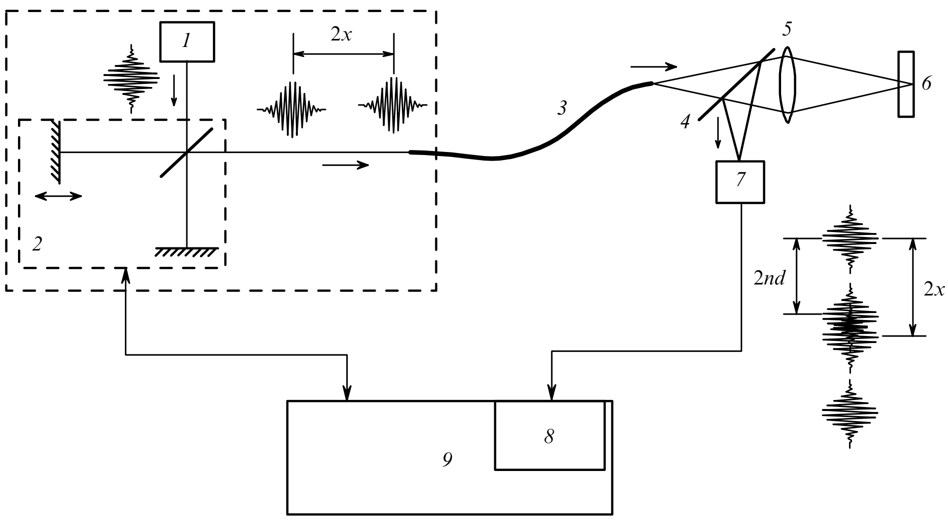


Figure 2. Experimental setup for measuring thickness of diamond plates by low-coherence interferometry: (*1*) low-coherence light beam; (*2*) tuneable interferometer; (*3*) optical fibre; (*4*) semitransparent mirror; (*5*) objective; (*6*) sample; (*7*) photodetector; (*8*) analogue-to-digital converter; (*9*) PC; x is the difference in lengths of the arms of tuneable interferometer; n is the refractive index of the sample and d is the sample thickness.

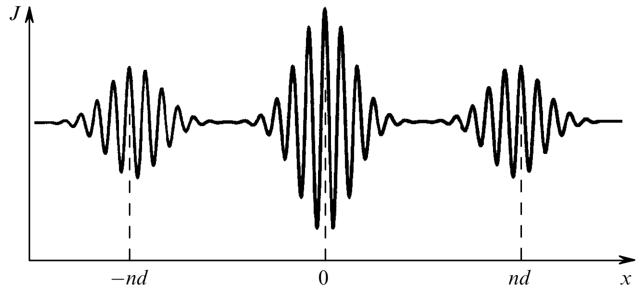


Figure 3. Interference signal in a low-coherence interferometer. J is the photoelectric current in the photodetector; x is the difference in lengths of the arms of the interferometer.

Significantly, the position of the interference peaks of the signal (see Fig. 3) does not depend on the total path length L. This renders the interferometer insensitive to a wide range of external perturbations and instabilities like temperature fluctuations of the length of fibre (*3*) and displacement of the sample along the probing laser beam [5].

As the broadband source of light, we used a SLD-381-MP2 superlum with $\lambda = 820$ nm and a coherence length ~ 15 μm. One of the interferometer mirrors was fastened to the membrane of an acoustic speaker that was used for scanning the path difference in the tuneable interferometer. The radiation was supplied to the sample through a 5-m long FS-SN-4224 single-mode optical fibre. The process of thickness measurement was completely automated, while a Pentium III PC was used for processing the interference signals and on-line display of the results of measurement.The system was capable of making 8 measurements per second, and the accuracy of measurements of the geometrical thickness of the plate was 1 μm in the range 50 – 500 μm of the measured thickness. The probing beam from the low-coherence interferometer was made coincident with the excimer laser beam on the sample surface being processed, which allowed a direct tracking of local variations of the sample thickness in the course of a multipulse laser processing.

3. Results and discussion

During the measurement of the thickness of polycrystalline plates, the magnitude of the observed interference signals is determined largely by the spatial structure of the interfering beams. Noncoincidence of the wavefronts of beams reflected at different surfaces of the sample is responsible for the emergence of an additional interference, i.e., the formation of dark and bright fringes in the cross section of the interfering beams. Upon an increase in the number of interference fringes at the aperture of the photodetector, the visibility of the lateral interference signals decreases (see Fig. 3), since a variation in the path difference between interfering beams leads to a displacement of the fringes over the aperture of the photodetector without changing the total optical power of the radiation incident on the photodetector.

During exposure of the sample surface to a beam of diameter smaller than, or of the order of, the characteristic size of the crystal grain faces, a pattern of elliptical interference fringes formed due to interference of two beams reflected from the smooth unprocessed surface of the sample and from the exposed crystallite face was observed at the surface being processed in our experiments. The width of the interference fringes decreased with increasing angle between the crystallite face and the unprocessed sample surface, as well as upon an increase in the sample thickness d. For the given parameters of the projection system and a minimum value of the signal-to-noise ratio admissible for thickness measurements with a given precision, there exists a maximum angle β between the face of the single crystal and the unprocessed surface, for which the sample thickness can still be measured. Thus, in the course of sample probing, the interference signal is obviously not observed at all points of the sample. However, there exist regions even in unprocessed plates (Fig. 4a) where measurements can be made.

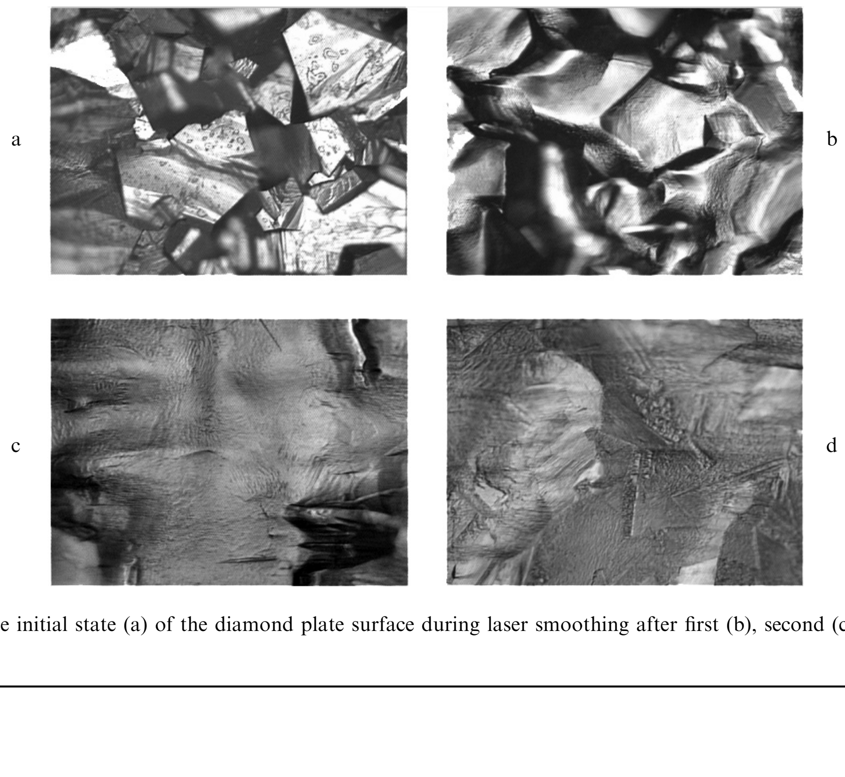


Figure 4. Evolution of the initial state (a) of the diamond plate surface during laser smoothing after first (b), second (c) and fourth (d) processing cycles.

For preset values of the thickness and signal-to-noise ratio, there exists an optimal magnification of objective (*5*), i.e. a ratio of the mode diameter of fibre (*3*) to the diameter of the focal spot on the sample, for which the angle β has its highest value. This is because the dependence of the visibility of interference signal on the magnification of the objective is determined by two competing effects. On the one hand, the width of the isoclinic rings increases with magnification of the objective, and hence it is more expedient to expose a plane-parallel sample to a parallel beam. On the other hand, isopachic fringes formed due to non-parallelism of the sample surfaces become thinner upon an increase in the magnification of the objective [6]. After optimisation of the projection system, the fraction of successful measurements in unprocessed plates was found to be $\sim 10\,\%$, which is sufficient for a preliminary evaluation of the surface thickness profile.

Laser polishing of polycrystalline diamond plates, whose various modes are described in detail in [2], considerably lowers the surface roughness to ~ 1 μm and below. In the experiments carried out by us, the dynamics of increase in the number of successful measurements was studied during processing that leads to a smoothing of the crystal grain tips right at the initial stage. Consequently, the surface at the tip is a plane parallel to the unprocessed surface of the plate. The sample, displaced according to a preset programme, was exposed to excimer laser pulses, the energy of the laser pulse increasing in each subsequent cycle of processing. The plate thickness was measured in the scanning mode of the probing beam over the sample surface after each cycle of laser smoothing. The distance between two neighbouring points on the sample surface at which measurements were made was equal to 20 μm.

The conditions of laser processing of a plate by KrF laser radiation are presented in Table 1. In the course of processing, the fraction of successful measurements of the sample thickness rose from 10 % (for an unprocessed plate) to 83 % (in the last processing cycle). The dynamics of surface smoothing and diamond etching is shown in Figs 4 and 5. One can see from the obtained results (see Fig. 5) that the investigated sample has a quite nonuniform thickness since it is cut from the edge of the original diamond disk of diameter 5 cm.

At the next stage, the sample profiles obtained after laser smoothing by using a low-coherence interferometer and a standard instrument (for this purpose, we used a Zygo NewView 5000 interference profile meter with a vertical resolution of 1 nm) were compared. The laser plate thickness before laser processing was 150 μm. Low-coherence interferometer measurements were carried out in a scanning mode by using a square raster with a 50-μm step. At 96 % of the points on the sample surface, the interference signal was strong enough for measuring thickness with a preset precision of 1 μm. A good agreement was observed between the thickness profile and the surface pattern measured by a low-coherence fibre optics interferometer and a profile meter respectively (Fig. 6). Thus, according to the profile measurement data, the maximum drop in the height of the relief was 14 μm, while the corresponding value obtained from fibre optics interferometry was ~ 13 μm. The thickness of the

Table 1.

Measurement cycle number	Laser polishing		Fraction of correct sample thickness measurements after laser processing (%)
	Pulse energy/mJ	Effective number of irradiation pulses at a point on the surface	
1	60	150	26
2	140	120	43
3	200	60	59
4	290	120	83

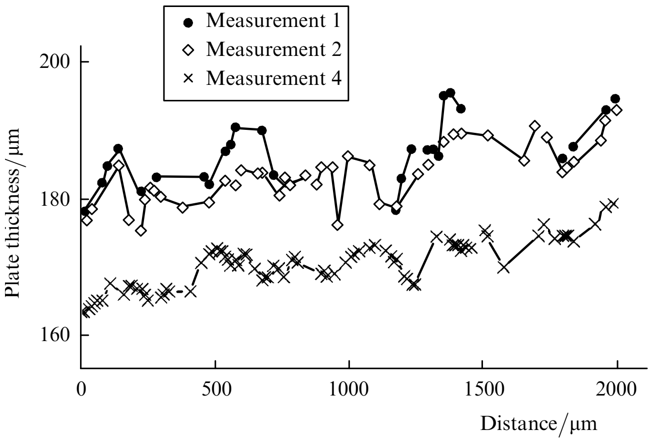
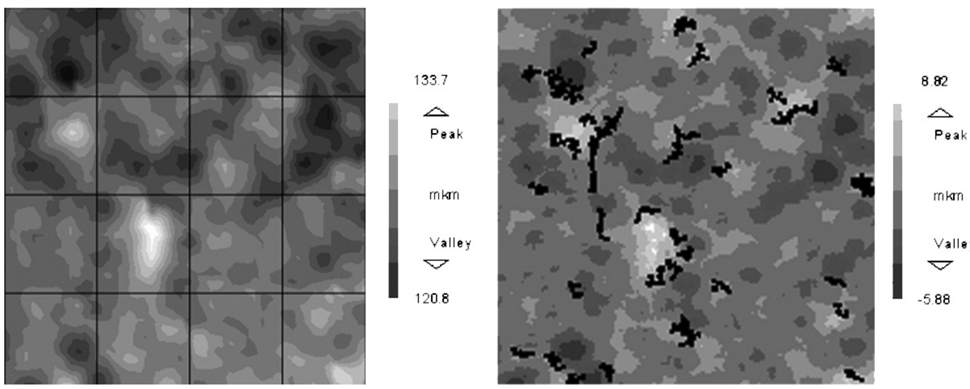


Figure 5. Modification of the diamond plate profile during several successive laser smoothing cycles.



a b

Figure 6. Relief of a polycrystalline diamond plate after laser smoothing (area 2×2 mm, roughness 1.4 μm, maximum drop in relief height 14 μm), recorded by low-coherence fibre optics interferometry (a) and by a Zygo NewView 5000 interference profile meter (b).

material removed as a result of laser smoothing was about 25 μm.

4. Conclusions

Our experimental studies have shown that it is possible to use low-coherence fibre optics interferometry for local contactless measurement of the optical thickness of polycrystalline plates of diamond with a surface roughness of the order of 30 μm, including the case when a laser-induced absorbing graphite layer is formed on the surface being processed. An automated experimental setup ensuring sample thickness measurement during the process of surface smoothing by a 248-nm KrF excimer laser beam has been developed. An accuracy of not less than 1 μm in on-line sample thickness measurements has been attained, thus paving the way for automating the processes of laser polishing, profiling, and microprocessing of polycrystalline diamond plates. The accuracy and speed of operation of the measuring system can be improved by at least an order of magnitude by using initially smooth surfaces and by employing new techniques of low-coherence interferometry [7].

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