Laser beam shaping for studying thermally induced damage

Bathusile N. Masina[a], Richard Bodkin[c], Bonex Mwakikunga[d] and Andrew Forbes[a,b†],
[a]CSIR National Laser Centre, P. O. Box 395, Pretoria 0001, South Africa
[b]School of Physics, University of KwaZulu-Natal, Private Bag X54001, Durban 4000, South Africa
[c]Element Six (Production) (Pty) Ltd, 1 Debid road, Nuffield, Springs 1559, South Africa
[d]CSIR National Centre for Nano-Structrured Materials, P. O. Box 395, Pretoria 0001, South Africa

ABSTRACT

This paper presents an implementation of a laser beam shaping system for both heating a diamond tool and measuring the resulting temperature optically. The influence the initial laser parameters have on the resultant temperature profiles is shown experimentally and theoretically. A CO_2 laser beam was used as the source to raise the temperature of the diamond tool and the resultant temperature was measured by using the blackbody principle. We have successfully transformed a Gaussian beam profile into a flat-top beam profile by using a diffractive optical element as a phase element in conjunction with a Fourier transforming lens. In this paper, we have successfully demonstrated temperature profiles across the diamond tool surface using two laser beam profiles and two optical setups, thus allowing a study of temperature influences with and without thermal stress. The generation of such temperature profiles on the diamond tool in the laboratory is important in the study of changes that occur in diamond tools, particularly the reduced efficiency of such tools in applications where extreme heating due to friction is expected.

Keywords: Laser heating, thermal stress, polycrystalline diamond tools.

1. INTRODUCTION

Temperature is difficult to measure with the accuracy and stability required for many potential applications and temperature sensors such as thermocouples depend on the attainment of thermal equilibrium with a surface via conductive or convective heat transfer[1]. These sensors are problematic to work with because they require intimate contact with the surface, which affects the local surface energy balance and thus temperature. The small sampling area of such sensors is also an issue and is affected by radiant energy exchange that can cause the measured temperature to differ from the surrounding surface[2]. An alternative to using temperature sensors is infrared thermometry which avoids the aforementioned problems by virtue of its all optical, non-contact properties. Since the work of Ming and Bassett[3], the use of the laser has become very common in high pressure and high temperature studies of materials because the temperature gradients and temporal fluctuations of temperature can be obtained and the emissivity on some metals or materials have been measured. The method involves pressurizing the sample to reach a high temperature in a solid or fluid medium when heating it with a laser. The thermal radiation is then collected over a range of wavelengths and the resulting spectrum is fitted with Planck's function. In order to use this method, the emissivity of a sample as a function of pressure, temperature and wavelength must be known[4-5].

In this paper we discuss the ability to heat a diamond tool sample by means of optical absorption of a CO_2 laser beam, and then measure the resulting temperature on the surface of the diamond tool optically based on blackbody principles. We also demonstrate the ability to heat a diamond tool sample with two laser beam profiles and two optical setups. A model for the temperature on the surface of the diamond tool was developed and we show that it agrees qualitatively with experimental data. In particular, we show that it is possible to engineer the boundary conditions and initial beam such that uniform temperature gradients can be created, thus allowing the study of thermal effects in the absence of thermal stresses. We make use of the known grey body emission from polycrystalline diamond (PCD) and we show that uniform temperature alone can account for significant structural changes in PCD.

2. BLACKBODY PRINCIPLE

All objects whose temperature is above zero degrees gives off thermal radiation in the form of electromagnetic waves in a wide range of wavelengths[6]. Thermal radiation is a direct result of the movements of atoms and molecules in a material which result in the emission of electromagnetic radiation, which carries energy away from the material surface. The concept that best describes thermal radiation is that of the blackbody[7] and forms the primary focus of this study. The blackbody is defined as a theoretical object that absorbs all radiation incident on it, regardless of frequency, and so it reflects no radiation and appears perfectly black. In practice however, no material has been found to absorb or emit all incoming radiation[5]. The blackbody has an emissivity of 1 because it absorbs or emits without reflectance or transmission while real bodies have an emissivity of less than 1[8]. Emissivity is defined as a measure of the ability of a body to radiate heat and is given by the ratio of the power radiated by the real body to the power radiated by the blackbody per unit area at the same temperature[8].

It is known that the blackbody radiates more intensity when it is hot than when it is cold and this is described by Stefan-Boltzmann's law which states that the total radiant heat energy emitted from a surface is proportional to the fourth power of its absolute temperature, where the absolute temperature refers to the temperature emitted by the object under study[9]. This law also describes how the amount of emitted radiation increases with increasing temperature and also the dependence on the composition of the object[9]. The emitted radiation is usually quantified according to its wave-like properties, and can be shown by the relative intensity as a function of wavelength or frequency[7]. Figure 1 show a typical blackbody spectrum which can be used to extract accurate temperature measurements of the objects under investigation. The colour of any particular kind of radiation is designated by a frequency or wavelength and it is for this reason that the blackbody principle can be used to measure temperature[6]. However, the emissivity must be known to convert radiant heat transfer measurements to temperature and it is important that emissivity be properly determined for the real material being studied in order to obtain accurate temperature measurements. The blackbody spectrum can be measured by using a standard spectrometer or thermal camera. The basic principle of the spectrometer case is that the emitted light from the blackbody is collected by an optical fibre and directed onto a diffraction grating that splits all the wavelengths up into a spectrum[10]. The basic principle of the thermal camera case is that the camera must be calibrated with a known blackbody and the measurement is based on the amount of light collected within the detection range[11]. Therefore by collecting the emitted light from the blackbody at each wavelength, it is possible to determine the temperature of the blackbody or of the object by fitting the blackbody spectrum to the measured light. The advantage of using the blackbody emission is that there is no physical contact with the object under study and the emissions used for temperature measurement is that of the object due to its temperature.

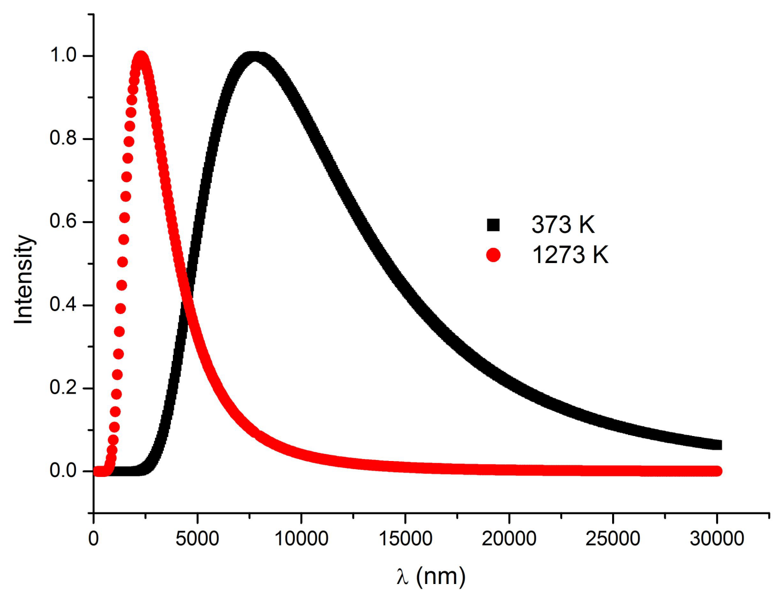

Figure 1: Typical blackbody spectrums for temperatures, 373 K and 1273 K, and a range of wavelengths.

3. TEMPERATURE MODEL

In order to find the dynamic temperature distribution on the surface of the sample, the heat diffusion equation was solved with a non-zero source term[12]:

$$\frac{\partial U(r,t)}{\partial t} - D\nabla^2 U(r,t) = Q(r)\,, \tag{1}$$

with diffusivity $D = k/\rho C_p$ and $U(r, t)$ is the temperature on the surface of the sample. Where ρ is the density, k is the conductivity, C_p is the heat capacity and $Q(r)$ is the source term. We solved the equation with cylinder coordinates ($U(r, \Theta, z)$) and we assumed that U is dependant only on r and t. Where r is the radial coordinate and t is time. The source term of this study was a continuous wave laser beam of Gaussian intensity distribution, which leads to a source term given by[13]:

$$Q(r) = \frac{I(r)\alpha}{\rho l C_p} \tag{2}$$

where $I(r)$ is the intensity profile of the laser beam. This was derived as follows; in order to raise the temperature of a body, to make it hotter, we must supply energy to it. The temperature of a body depends not only on the amount of energy supplied to it, but also on its size and nature. In order to be able to compare the abilities of different materials to absorb energy we use the quantity specific heat capacity. In other words, the amount of heat gained or lost is given by[14]

$$Q = mC_P\Delta T\,, \tag{3}$$

where Q is quantity of heat; m is mass of a material; C_p is the specific heat capacity and ΔT is the change in temperature. For an extremely small temperature change dT and corresponding quantity of heat dQ, equation (3) is written in the form,

$$dQ = mC_P dT \tag{4}$$

and at the rate of time, equation (4) is written in the following form,

$$\frac{dQ}{dt} = mC_P\frac{dT}{dt}\,. \tag{5}$$

Let $Q = E$, $T = U$ and equation (5) is written as,

$$\frac{dE}{dt} = mC_P\frac{dU}{dt}\,, \tag{6}$$

where $m = \rho v$; ρ is the density and v is the volume. Rearranging the terms of equation (6); we obtain:

$$\frac{\frac{dE}{dt}}{\rho v C_P} = \frac{dU}{dt} \tag{7}$$

The volume is given by $v = lA$, where l is the length and A is the area. Rearranging the terms of equation (7); obtain:

$$\frac{\frac{dE}{dt}}{\rho l A C_P} = \frac{dU}{dt} . \tag{8}$$

Since the intensity is given by $I = \frac{P}{A}$ and the power is given by $P = \frac{dE}{dt}$, equation (8) becomes:

$$\frac{I(r)}{\rho l C_P} = \frac{dU}{dt} . \tag{9}$$

Therefore the source term is given as

$$Q(r) = \frac{dU}{dt} = \frac{I(r)}{\rho l C_P} . \tag{10}$$

Note that not all the laser intensity is absorbed by the material and so we modified the equation to include the absorption coefficient α and equation (10) becomes,

$$Q(r) = \frac{I(r)\alpha}{\rho l C_P} , \tag{11}$$

For a Gaussian laser beam $I(r) = \frac{2P_0 \exp\left(\frac{-2r^2}{\omega^2}\right)}{\pi\omega^2}$ and by substituting the intensity, the source term is given as:

$$Q(r) = \frac{2P_0\alpha \exp\left(\frac{-2r^2}{\omega^2}\right)}{\rho l C_P \pi\omega^2} . \tag{12}$$

The source term depends on the radial coordinate *r*, the total power of the laser P_0, the beam size ω and also on the absorption coefficient α. Varying the total power of the laser, the beam size and the radial coordinate we can vary the source term. The source term is directly proportional to the total power of the beam, meaning that an increase of the total power, results in an increase of the source term. In the case when the flat-top beam is used, the source term is given by[15]:

$$Q(r) = \frac{P_0\alpha}{\rho l C_P \pi\omega^2} . \tag{13}$$

This problem can be formulated in terms of the Green's function approach, which leads to an integral solution given by[16]:

$$U(r,t) = \int_0^t \int_0^a Q(\xi,\tau) G(r,\xi,t-\tau) d\xi d\tau , \tag{14}$$

$$G(r,\xi,t) = \frac{2}{a^2}\xi + \frac{2}{a^2}\sum_{m=1}^{\infty}\frac{\xi}{J_0^2(\alpha_m)}J_0\left(\alpha_m\frac{r}{a}\right)J_a\left(\alpha_m\frac{\xi}{a}\right)\exp\left(-\frac{D\alpha_m^2 t}{a^2}\right). \quad (15)$$

The boundary conditions of this study are: the initial temperature profile on the surface of the material is at room temperature ($U(r, 0) = 300K$), secondly, the temperature profile on the edge of the material is at room temperature or is constant ($U(a, t) = 300K$) and also the other boundary condition is that there is zero heat flow on the material ($\frac{\partial U}{\partial r} = 0$) at $r = a$). The α_m terms are positive zeros of the first-order of the Bessel function, $J_1(\alpha_m) = 0$. Here a is the sample radius, J_x refers to a Bessel function of order x, and r is the radial coordinate.

4. LASER BEAM SHAPING AND HEATING

A laser-based system is ideal for creating the heat required to raise the temperature of the object under study. A laser beam is focused onto the absorbing object as depicted in figure 2, and the absorbed laser radiation will cause the object temperature to increase. During the laser heating process, the object heats up, and so the temperature rises until a steady state is reached and that is when the energy being delivered by the laser is equivalent to the energy lost to the surroundings. The emission spectrum from the object is measured during the above process, and so the temperature rise as a function of time across the object can be monitored. The advantage of using the laser to raise the temperature of the object is that the laser beam can be easily adjusted and controlled to deliver intense heat over a small area or a large area of the object for desired periods of time by varying the laser beam parameters such as beam spot size and laser power. The laser power delivered to the sample can also be varied using a polarization-based attenuator, while the size of the beam at the sample could be varied by simply moving the sample in and out of the focal plane of the lens, thus varying the temperature of the object. The laser beam intensity profile can also be shaped to allow for the control and uniform distribution of the intensity over the surface of the sample.

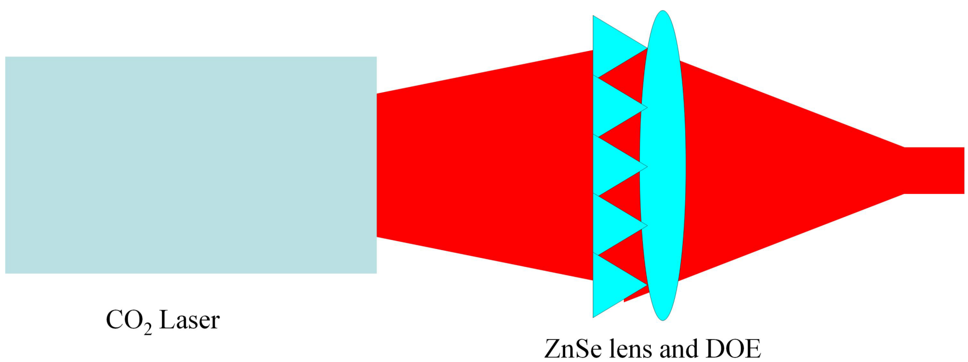

Figure 2: A schematic diagram of the laser delivery system for the laser heating of the sample and measuring the resultant temperature profile.

Laser beam shaping has been investigated over many years for industrial, military, medical and research applications such as laser therapy and materials processing[17]. The theory for beam shaping has been outlined in detail by Dickey[18]. A common requirement for these applications is a laser beam profile that is uniform over some cross-section. Laser beam shaping is the process of redistributing the irradiance and phase of a beam of optical radiation. The irradiance distribution and the phase of the shaped beam is a major factor in determining the propagation properties of the laser beam profile in the beam shaping method. In order to shape a laser intensity profile, the spatial phase of the beam needs to be adjusted before propagating the laser beam some distance to the target. The laser beam intensity profile can be shaped with either amplitude or phase modulation of the beam by using diffractive optical elements (DOE)[19], aperturing of the input laser beam[20], etc. Amplitude modulation is effective in beam shaping but has the drawback of wasting significant amounts of the laser energy while the phase modulation is much more efficient for commercial uses and is virtually lossless. In the case of the aperturing of the input beam method, the beam is expanded and an aperture is used to select a suitably flat-top portion of the beam. The shaped laser beam profile may be arbitrary, including rectangular, circular, triangular, ring shaped and flat-top to name but a few. In this study, we used the DOE pictured in figure 3 as a phase element in conjunction with a Fourier transforming lens to transform a Gaussian beam profile into a flat-top beam profile. A Fourier transforming lens is placed directly behind the DOE as was illustrated in figure 2, in order to take the Fourier transform of the incident Gaussian beam profile and produce a flat-top beam profile at the focal plane of the lens. This method is only capable of creating a single intensity profile (thus a flat-top beam profile) and is usually very sensitive to the input beam characteristics.

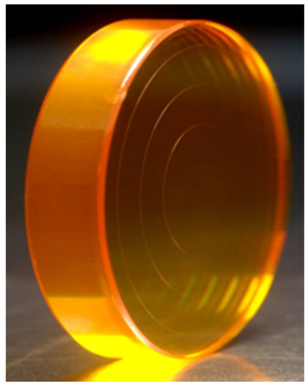

Figure 3: A photograph of the diffractive optical element that was used in this study.

5. DIAMOND TOOL

One of the questions that we address here is whether thermally induced problems in some materials arise as a result of how hot the object is and is the thermal gradient on the object caused by not having the same laser intensity profile everywhere? In this work we have chosen to study a synthetic diamond tool which has found wide commercial acceptance in the mining industry since its introduction more than a decade ago[21]. The drill bits used in mining are outfitted with the diamond tool for a significant portion of the total footage drilled, with the popularity due to their effectiveness in drilling soft to medium formations at relativity high penetration rates[21]. However, the drill bits reach very high temperatures during a typical drilling process due to friction, with the efficiency of the material decreasing rapidly at temperatures exceeding 700–750^{o}C, and thus damage is induced by thermal stress[22]. The diamond tool comprises of a polycrystalline diamond (PCD) layer on a supporting tungsten carbide (WC) substrate that is sintered at a high temperature and high pressure (HTHP) and the origin of this diamond has been discussed previously[23]. The HTHP diamond tool used in this study was deposited on a 15 mm diameter cylindrical alloy substrate containing tungsten carbide (WC) with trace elements of iron (Fe) and cobalt (Co). The total thickness of the sample was 15 mm, where WC is 12 mm thick and PCD is 3 mm thick, as shown in the inset of figure 4.

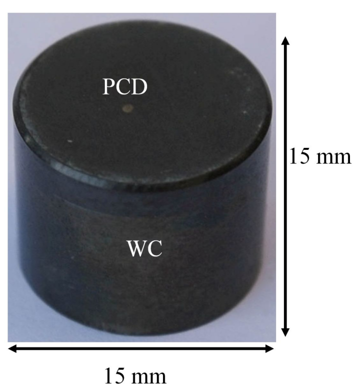

Figure 4: The diamond sample.

6. EXPERIMENTAL SETUP

The experimental system for the delivery of the laser beam was shown in figure 2. A continuous wave (cw) CO_2 laser (Synrad D48-2-115) was used as the laser heating source in the experiment. A Helium Neon laser was aligned to be co-linear with the CO_2 beam to facilitate alignment of the invisible infrared CO_2 beam throughout the optical system. The DOE element was designed to work at a specific wavelength of 10.6 μm and a beam radius of 7 mm. The laser beam was delivered through suitable optical elements to produce a beam radius of 7 mm, with a near flat wavefront at a focusing lens (ZnSe) of a focal length of a 250 mm. The DOE beam shaping element and a Fourier transforming lens were placed at the position where the 7 mm beam radius was located and the Gaussian beam could be reshaped to a flat-top beam at the same plane after the lens, as shown in figure 5 (a) and figure 5 (b), respectively. The power delivered to the sample could be varied between x-40 W with the polarization-based attenuator, while the size of the beam at the sample could be chosen depending on the distance after the lens. An 88% reflecting beam-splitter allowed continuous monitoring of the laser power over the duration of the experiment and the laser beam profiles at the sample were measured with a pyro-electric camera (Spiricon Pyrocam III).

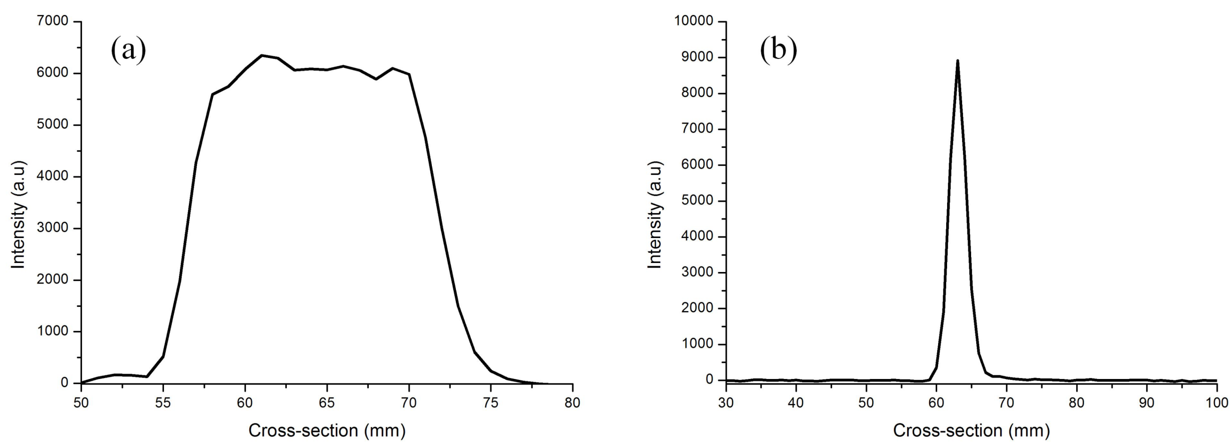

Figure 5: (a) The Gaussian beam profile, (b) the flat-top beam profile.

We carried out two sets of experiments: (1) in the first experiment, the temperature across the object was kept constant, with no gradient and therefore no stresses, and (2) in the second experiment, a temperature gradient was applied across the object, with high stresses even at relatively low temperatures. The second experiment is achieved by considering how the object will dissipate heat if subjected to a heating source such as a laser beam. We created two simple holders for the object so that the two sets of experiments can be realized. First, the object is housed in a cylindrical stainless-steel holder padded on the inside with an insulator to prevent heat flow or heat losses through the circumference, thus mimicking the zero-heat-flow boundary condition scenario as shown in figure 6 (a). This means that only the radiation emitted will be measured and so the object quickly develops a uniform temperature even if the heating mechanism is not uniform across the sample. Second, the object is housed in a copper block that is water cooled, so that the boundary is always at a constant temperature no matter what the heating looks like as shown in figure 6 (b). This holder results in a very strong thermal gradient across the object. The diamond tool sample was laser heated with both laser beam profiles and two optical setups and then the resultant temperature profile was measured. During heating, the resulting grey body emission from the sample was collected on an IR camera (Xenlcs Gobi-1152) and converted into a temperature profile using the blackbody principles mentioned in section 2.

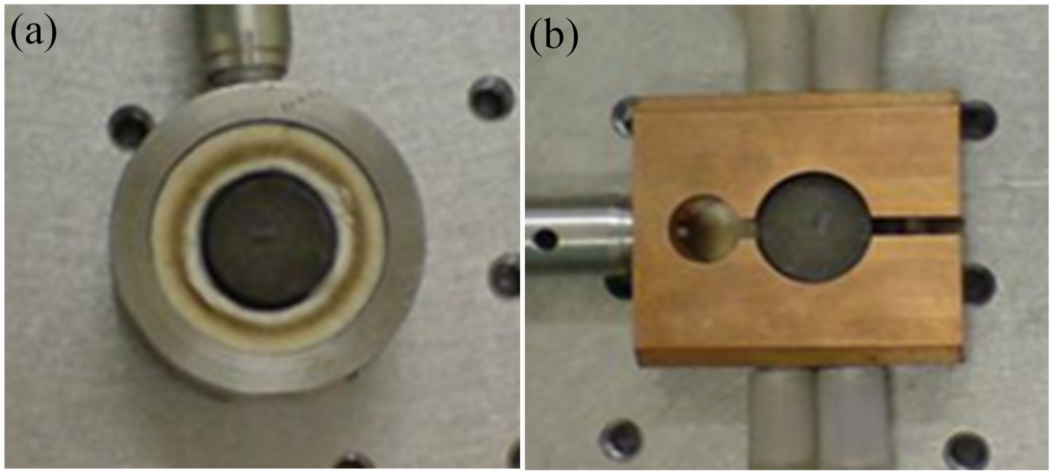

Figure 6: (a) The insulator holder with the diamond sample inside it, (b) The copper-cooled holder with the diamond sample inside it.

7. RESULTS AND DISCUSSION

Due to the boundary condition of zero-heat-flow achieved by the setup in figure 6 (a), the sample takes on a uniform temperature profile even when the source term is not uniform. The predicted profiles for a Gaussian source term are shown in figure 7 (a) together with the measured profiles in figure 7 (b) and similar profiles are found with the use of the flat-top beam. The results show that even with a Gaussian laser beam profile, this setup allows a uniform temperature profile across the PCD sample. Due to the boundary condition of the temperature profile at the edge of the sample being room temperature achieved by the setup in figure 6 (b), the sample takes on a gradient temperature profile. The predicted profiles for a Gaussian source term are shown in figure 8 (a) together with the measured profiles in figure 8 (b). The results show that with a Gaussian laser beam profile, this setup allows a gradient temperature across the PCD sample. Previously, it has been shown[24] that laser heating does not result in graphitization of the PCD, but rather cobalt and tungsten oxides form on the diamond surface, as shown in Figure 9. In such experiments, the thermal gradients could not be controlled, nor was there a suitable system in place for measuring the resulting temperature profile across the sample.

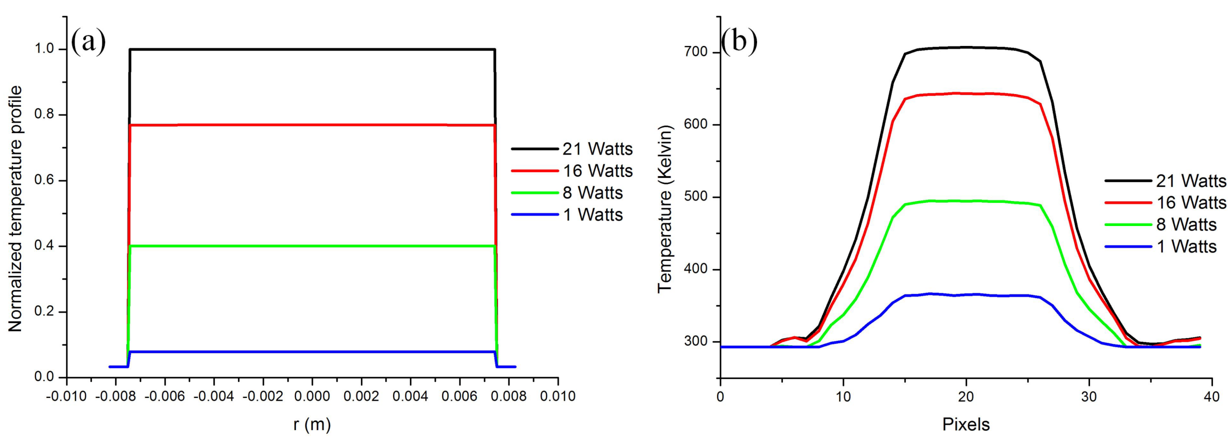

Figure 7: The insulator holder results, (a) temperature profile model, (b) temperature profile across the sample surface per laser beam power or time for the sample that was laser heated with the Gaussian laser beam profile and flat-top laser beam profile.

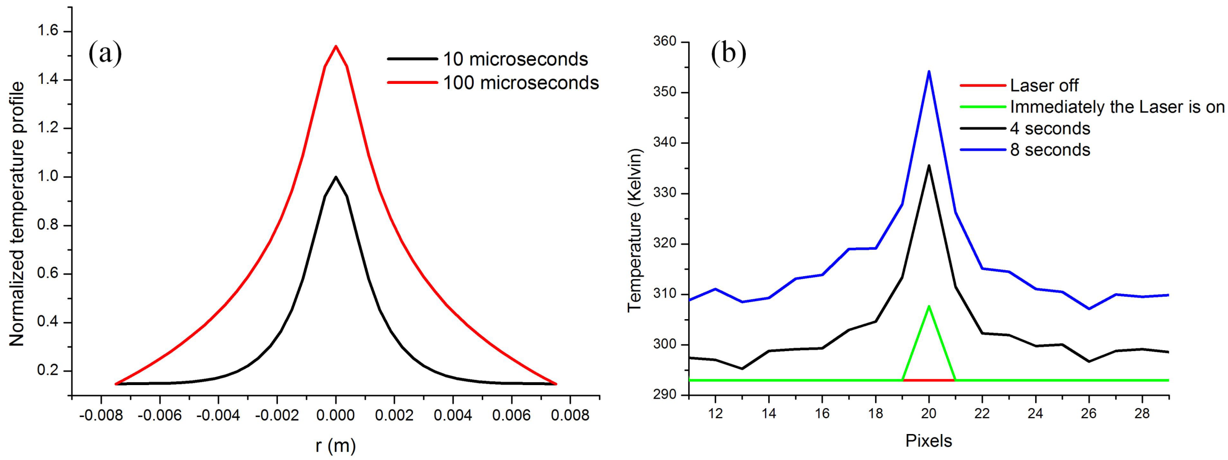

Figure 8: The copper-cooled holder results, (a) temperature profile model, (b) temperature profile across the sample surface per laser beam power or time for the sample that was laser heated with the Gaussian laser beam profile.

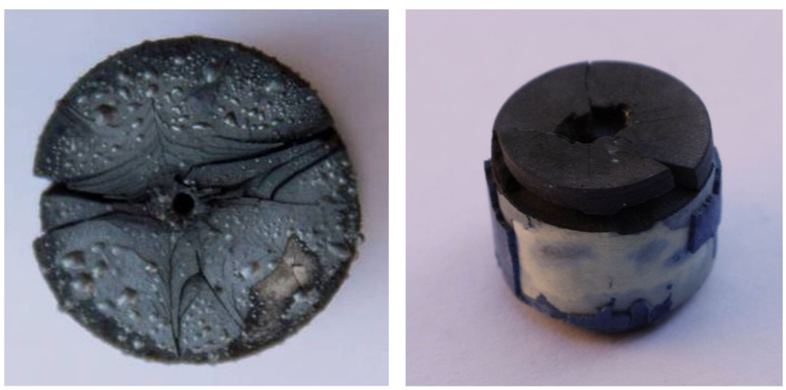

Figure 9: Diamond tools damaged due to the laser heating with both physical and chemical changes evident.

Figure 10 and figure 11 shows a comparison of the Raman spectra and SEM micrographs taken on the surface of the PCD layer. Raman spectra were taken on the PCD layer surface before and after laser heating for 45 minutes. The sample was heated for 45 minutes at a laser beam power of 26 W and laser beam radius of 0.7 mm. The temperature was determined to be 681 Kelvin by collecting the emitted emission of the diamond tool using the infrared camera. The infrared camera used the emission to determine the temperature using the blackbody principle mentioned above. It is evident that there is no graphitisation on the surface of the PCD layer due to the temperature since there is no peak for graphite on the Raman spectra. However there are Raman shifts for the peaks of the oxides of W and Co as seen in figure 10. This was also observed on the SEM micrograph of figure 11. The SEM micrographs show that the Co and W migrated on the PCD layer and microstructure was formed due to laser heating or temperature. There is a small Raman shift of the diamond peak (1338 cm^{-1} before and 1335 cm^{-1} after laser heating for 45 minutes), compared with pure diamond (1332 cm^{-1})[25]. Cappelli *et. al*[26] also observed this similar Raman shift of the diamond peak after growing the diamond tool using CVD method. It was suggested that this could be due to some compressive deformation coming from the thermal expansion mismatch between diamond and the hard metal WC substrate ($\alpha_{diamond} \sim 0.8\text{-}1 \times 10^{-6}\ K^{-1}$, compared with $\alpha_{WC.Co} \sim 4.5\text{-}\ 5.4 \times 10^{-6} K^{-1}$). In our case, the compressive deformation should be coming from the doping or alloying effects of the Co and W diffusion into diamond. All the Raman shifts were identified based on previous work[27].

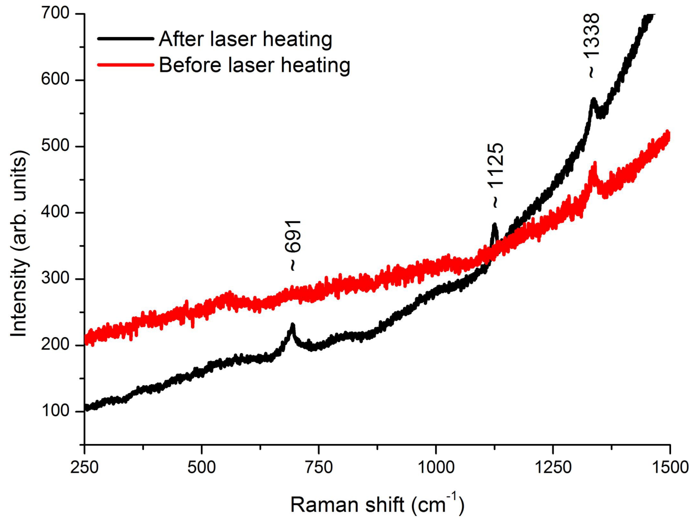

Figure 10: Initially the PCD layer shows a Raman shift around 1338.2 cm^{-1} which is a diamond peak and after laser heated for 45 minutes, the PCD layer shows some Raman shift of Co or W oxides and the diamond peak has shifted to 1335cm^{-1} on the diamond layer caused by the laser heating. The temperature was determined to be 681 Kelvin.

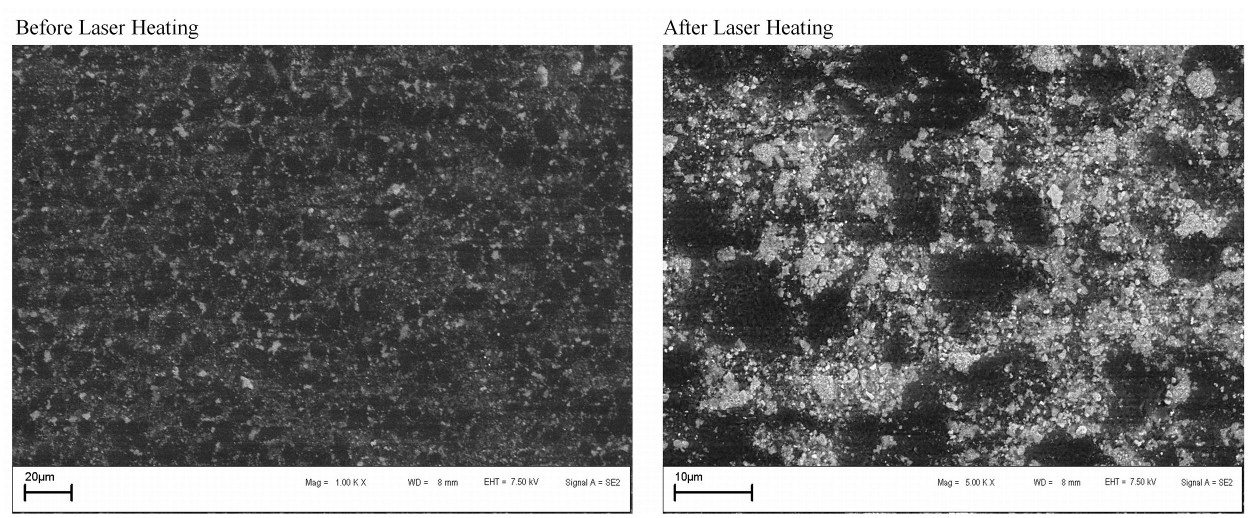

Figure 11: SEM micrographs for the initial sample and that after the sample have been laser heated for 45 minutes. The temperature was determined to be 681 Kelvin. Initially the diamond sample had a trace amount of Co, on the PCD layer as the EDS analysis indicated which is not shown here. The Co is presented with the lighter phase on the morphology and the darker phase is the carbon (C). After laser heating for 45 minutes the diamond layer shows that the heating melted the diffused Co and W on the PCD layer forming oxide microstructures.

Comparing the average and peak temperature values, the thermally induced stresses in the diamond are minimised, yet the temperature experienced by the diamond can be arbitrarily large, thus allowing a controlled study of the physical and chemical changes in diamond due to heating alone. Previously, such studies were conducted in hot-filaments[28], diamond anvil cells (DAC)[29] and microwave plasma[30]. In this work, the same effect was created with the added advantage of localised heating down to the diffraction limit of the laser beam spot size, thus opening the way to controlled spatial studies on diamond heated samples.

8. CONCLUSION

We have demonstrated a laser beam shaping system for heating and then measuring the temperature profile of a particular diamond tool sample. However this system can be use for any material. We successfully raised the temperature profile of the sample in a controllable manner over a wide range of laser powers and showed that a uniform temperature profile across the sample could be engineered. The experimentally measured profiles are in agreement with that predicted theoretically, while we can measure the temperature of a sample to within 1 Kelvin from just above room temperature to over 1000 Kelvin without contact with the sample. The creation of such temperature profiles allows a study of temperature influences without thermal stress, adding a valuable tool for those wishing to execute controlled material heating studies.

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REFERENCES

[1] Fuchs M., "Canopy thermal infrared observations", Remote Sens. Rev. 5, 323 - 333 (1990).

[2] Baker J.M., Noman J.M. and Kano A., "A new approach to infrared thermometry", Agr. And Forest Meteorology. 108 (4), 281 - 292 (2001).

[3] Dubrovinsky L.S., Saxena S.K., "Emissivity measurements on some metals and oxides using multi wavelength spectral radiometry", High Temperature - High Pressure 31(4), 393 - 399 (1999).

[4] Ming L.C., Bassett W.A., "Laser heating in the diamond anvil press up to 2000 oC sustained and 3000 oC pulsed at pressures up to 260 kilobars", Rev. Sci. Instrum. 45(9), 1115 - 1118 (1974).

[5] Bassett W.A., Ming L.C., "Disproportionation of Fe2SiO4 to 2FeO+SiO2 at pressures up to 250 kbar and temperatures up to 3000 oC", Phys. Earth Planer. Inter., 6, 154 - 160 (1972).

[6] Thomas S.K., [Blackbody theory and quantum discontinuity, 1894 - 1912], University of Chicago Press, Chicago, 206 - 228 (1978).

[7] Harrison T.R., [Radiation pyrometry and its underlying principles of radiant heat transfer], John Wiley an sons, 5 (1960).

[8] Mehra J., Rechneberg H., [The historical development of quantum theory], Springer, 1 (1982).

[9] Dougal R.C., [The presentation of the Planck radiation formula], Phys. Educ., 11, 438 - 443 (1976).

[10] http://www.oceanoptics.con/Products/usb2000+rad.asp

[11] http://www.xenics.com/

[12] Arfken G.B., Weber H.J., [Mathematical methods for physicists 4th edition], 385 (1995).

[13] Masina B.N., "Optical determination of the temperature of a laser heated industrial diamond",MSc Dissertation, University of Zululand (http://uzspace.uzulu.ac.za), 39 - 56 (2008).

[14] Young H.D., [University physics 8th edition], Addison-Wesley Publishing Company, 5290 (2008).

[15] Bernhardi E.H., Forbes A., Bolling S., Esser M.J.D., "Estimation of thermal fracture limits in quasi-continuous-wave end-pumped lasers through a time-dependent analytical model", Opt. Express 16, 11115 - 11123 (2008).

[16] Barton G., [Elements of green's functions and propagation], Oxford University Press, 41 - 75 (1995).

[17] Lee W., "Method for converting a Gaussian laser beam into a uniform beam", Appl. Opt., 22, 3644 - 3647 (1983).

[18] Dickey F.M., Holswade S.C., [Laser Beam Shaping: Theory and Techniques], Marcel Dekker, New York, 1 (2000).

[19] Kanzler K., "Diffractive laser beam shaping for material processing using a CO2 laser", Proc. SPIE 5525, 64 - 75 (2004).

[20] Degama M.P., Forbes A., "Wavelength-independent laser beam shaping", Proc. SPIE 7789, 1 - 4 (2010).

[21] Hong S., Akaishi M., Kanda H., Osawa S., Yamaoka S., "Dissolution behaviour of fine particles of diamond under high pressure sintering conditions", J. Mater. Sci., 10, 164 - 166 (1991).

[22] Wentorf R.H., DeVries R.C., Bundy F.P., "Sintered superhard materials", Sci., 208, 873 - 880 (1980).

[23] Prakash V., "Temperature distribution in synthetic diamond cutters during orthogonal rock cutting", SPS drilling engineering, 137 - 143 (1989).

[24] Masina B.N., Forbes A., Ndwandwe O.M., Hearne G., Mwakikunga B.W., Katumba G., "Thermally induced defects in a polycrystalline diamond layer on a tungsten carbide substrate", Phys. B. 404, 4485- 4489 (2009).

[25] Catledge S.A., Vohra Y.K., Ladi R., Rai G., "Micro-Raman stress investigations and X-ray diffraction analysis of polycrystalline diamond (PCD) tools", Diamond and Related Mat., 5, 1159 - 1165 (1996).
[26] Cappelli E., Pinzari F., Ascarelli P., Righini G., "Diamond nucleation and growth on different cutting tool materials: influence of substrate pre-treatments", Diamond and Related Mat., 5, 292 - 298 (1996).
[27] Diaz-Reyes J., Dorantes-Garcia V., Perez-Benitez A., Balderas-Lopez J.A., "Obtaining of films of tungsten trioxide (WO3) by resistive heating of a tungsten filament," Superficies Vacio, 21 (2), 12 - 17 (2008).
[28] Lee Y.H., Bachamann K.J., Glass J.T., LeGrice Y.M., Nemanich R.J., "Vapor deposition of diamond thin films on various substrates ", Appl. Phys. Lett., 57, 1916 - 1919 (1990).
[29] Heinz D.L., Sweeney J.S., "Al laser heating system that stabilizes and controls the temperature: diamond anvil cell applications", Rev. Sci. Instrum., 62, 1568 - 1575 (1991).
[30] Stuart S.A., Prawer S., Weiser P.S., "Growth-sector dependence of fine structure in the first-order Raman diamond line from large isolated chemical-vapor-deposited diamond crystals", Appl. Phys. Lett., 62, 1227 - 1230 (1993).