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CHARACTERISATION OF A Q-SWITCHED TEM_{00} Nd:YAG LASER FOR PROCESSING SINGLE AND POLYCRYSTALLINE DIAMONDS

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In the present investigation, a Q-switched Nd:YAG laser is characterized and used to study the various aspects of single and polycrystalline diamond processing. The experimental setup mainly consists of a Q-Switched Nd: YAG laser at 1064nm with a maximum average power of 18 W at 4 KHz.Inorder to check the accuracy of the focused laser beam and to find out an exact diamond cutting operating power and frequency range, the variation of beam diameter at the output coupler and thermal lens focal length at different Nd doping concentration of active medium and energy density at the work piece are found out . The diamond cutting is performed by making the “V” shaped groove with various opening angle. The variation of weight loss of diamond during cutting and time taken for the process are noted. The Q-Switched Nd:YAG laser system is showing very good performance in terms of peak to peak out put stability, minimal spot diameter, smaller divergence angle, higher peak power in Q-Switched mode and good fundamental TEM_{00} mode quality for processing natural diamond stones. Minimum weight loss, less micro-cracks and good surface quality of diamonds are achieved.

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1. Introduction

The impact of laser technology in the processing of naturally grown single and poly crystalline diamonds has revolutionized the field in many respects [1,2]. There are many advantages for laser processing of diamonds. The cut can have a very narrow kerf width which leads to reduced weight loss of material which is very important in diamond cutting as it is a precious jem stone. Very narrow spot diameter of laser beam and the non-contact nature of cutting scheme reduces the material loss during diamond processing. The cut edge is smooth and clean and requires no further cleaning or surface treatment. The heat affected zone will be of small depth. Many diamonds with distorted growth, such as graining or twinning, cannot be cut by conventional mechanical saw means because of the changes in cleavage and sawing planes they contain. The laser saw can also be of help in those situations where the material has included crystals of diamond along the plane selected for sawing. Given our knowledge that diamond has conventional primary sawing directions parallel to the theoretical cube faces and secondary sawing directions parallel to the theoretical dodecahedral faces, and that the crystallographic orientation of the included crystals of diamond is random to the host crystal in most instances, it is evident that the different sawing planes make conventional sawing next to impossible. In this case the vibrations produced when the blade reaches the included crystal can cause the crystal to shatter. Even if the stones do not shatter, the cutting time may easily be twice or three times that of the normal stone, extending into many days or even weeks.

Nd:YAG lasers are playing a vital role for kerfing and sawing natural, polycrystalline and synthetically grown CVD diamonds. All applications of the laser in material processing are based

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mainly on the local conversion of the radiation energy into heat. In the present study we have used the vaporization cutting technique using Nd:YAG laser with intensity range 10^6-10^7W/cm^2[3]. In this scheme, the focused laser beam heats up the surface to the boiling point and generates a keyhole. The keyhole causes a sudden increase in the rate of absorption due to multiple reflections leading to quick deepening of the hole. As it deepens, vapor is generated. This vapor escapes blowing ejecta out of the kerf and stabilizing the molten walls of the hole [4,5]. When the laser is used in the CW form, it will not machine the diamond, even when focused. It will simply heat the diamond sample. So we have to Q-Switch the laser beam at a particular repetition rate [6,7]. This is achieved by acousto-optic Q-Switch used internally. Thus the output of the laser becomes pulsed. These laser pulses really contain very little energy but they occur for short periods of time that the peak powers in excess of 40 kW can be produced which are sufficient for removing the material. In the present investigation both CW and Q-Switched pulsed output from the laser are optimized for diamond processing.

1.1 Processing of diamonds using lasers

Having found a rough stone, the way it is then "cut" is vital to the value of the diamond. Each stone has to be individually cut and polished to produce a number of facets to create the gem diamond. A good cut produces facets whose placement and angles are mathematically accurate to maximize the diamond's brilliance [8]. The way a diamond sparkles in the light is called its brilliance and fire. But when light strikes a diamond, part of the ray is reflected from the surface. This is called external reflection. The other part of the ray enters the diamond and, as it does so, it bends due to the greater optical density of a diamond. This is called refraction. The light is then reflected from the internal surfaces of the diamond - which is internal reflection [9]. The ray then emerges from the top of the diamond where, once again, it is bent or refracted and is separated into the colors of the spectrum. It is this dispersion that gives the diamond its fire. A well cut or faceted diamond, regardless of its shape, scintillates with fire and light and offers the greatest brilliance and value. While nature determines a diamond's clarity, carat weight and color, the hand of a master craftsman is necessary to release its fire, sparkle and beauty. When a diamond is cut to good proportions, light will reflect from one mirror-like facet to another and disperse through the top of the stone, resulting in a display of brilliance and fire. The Ideal cut Diamond describes a round brilliant diamond that has been cut to exact and mathematically proven proportions. It's symmetry, with 58 exactly placed facets, produces the ultimate in luster and beauty. When a diamond is cut to the ideal proportions, all of the light entering from any direction is totally reflected through the top and is dispersed into a display of sparkling splashes and rainbow colors. Light entering the diamond reflects internally from facet to facet and is reflected back through the top only, creating maximum brilliance [10]. In order to achieve a well-cut of diamond, we are utilizing the unique properties of laser light. As a typical laser beam has a diameter of a few millimeters, it is relatively easy to collect all the light produced and to focus it to a spot with a diameter of a few wavelengths of the laser light in question. In the present case Nd:YAG laser produces a focal spot diameter of only a few microns. As a consequence of this ability to focus, even an Nd:YAG laser of medium power can produce focused peak power densities of over 500 MW/cm^2. Such very high focused peak power densities result in sufficient thermal energy being coupled into the diamond surface to graphitize and then to vaporize it in the focal region. Therefore the output of a laser beam which is a near parallel beam has to be changed in shape to make it suitable for cutting diamonds .But such a beam cannot make a parallel-sided cut as obtained with a mechanical saw. The laser saw cuts a “V” shaped slot. The kerf opening of this “V” shape is proportional to the depth of the cut required. The amount of material which is removed is a function of the square of the depth.

All these depends on the quality of the laser beam used for sawing. The quality of beam produced by a laser depends on the mode structure produced within the resonator. The fundamental TEM_{00} mode laser beam has been used for the present investigations to get better results [11]. The mode quality is controlled by the quality of laser crystal, positioning of optical components in the optical rail and the diameter of the mode controlling aperture in the resonator. The smaller is the aperture diameter better will be the beam quality but with appreciable reduction in output power. For finest cut and lowest weight loss TEM_{00} mode is required. This polarized fundamental mode allows the narrowest theoretical cut to be produced with steeper walls than can be achieved with multi mode laser [12,13,14]. One major problem which one faces in using Nd:YAG lasers for diamond machining is that the absorption of 1064 nm wavelength laser in diamond is very negligible. This is simply overcome by inking or painting the diamond to create an absorbing surface. Once the laser is absorbed in this surface, it heats and graphitizes the underlying diamond and the process then becomes self-sustaining.

2. Experimental

In the present investigation, the processing of natural diamonds of different origins, grades and sizes are performed using an acousto-optically Q-switched Nd:YAG laser. The laser design, development and the characterization of different parameters are also performed. The various aspects of laser diamond processing at 1064 nm have been investigated. The experimental set up used for laser sawing of diamond is shown in Fig. 1.

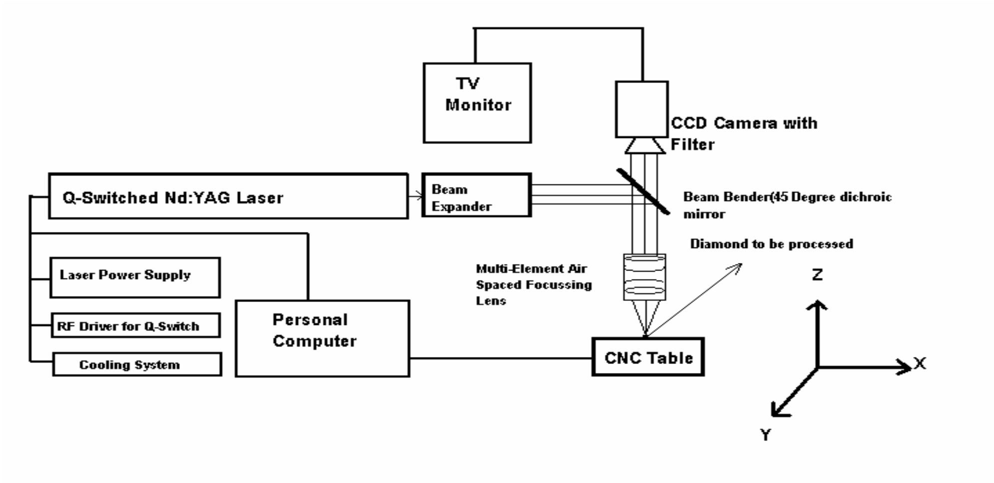


Fig. 1. Experimental set up for Laser processing of diamond crystals.

A Q-Switched Nd:YAG laser (1064 nm) at a repetition rate of 4 kHz and avearge power of 20 W is used and the maximum CW power is obtained as 30 W. Even though we are using the work station in the near field of laser source, the divergence of the output beam can cause certain adverse effects on focused spot size. In the present application the beam divergence should be as small as possible to get a small spot size to reduce weight loss of material during the cutting process. In order to reduce the beam divergence, the laser beam is expanded using a beam expander with expansion ratio equal to 1:8. The expanded beam is reflected by an angle of 90 degrees by a dichroic mirror placed at 45 degrees to the axis of beam. The laser beam after bending 90 degrees is focused by a multi-element focusing lens onto the diamond sample so that the focused spot size is ~20 μm. The diamond sample is fixed over the CNC table which is capable of moving in all the three co-ordinate axes by receiving control signals from the computer .The Power supply module and RF driver stage(for Q-switch) are also connected to the system. Necessary cooling arrangement for arc lamp and laser crystal is also incorporated.

2.1 Characterization of Nd:YAG laser for diamond processing

A plane parallel resonator with a mirror separation of 860 mm is configured in the stable region of stability diagram for the laser. Single elliptical cavity has been used for pumping which is very efficient [15]. The dimensions of YAG rod used is 3ϕ × 108 mm.The carrier frequency used in the RF driver for Q-Switch is 27.12 MHz and modulating frequency range is 0-100 KHz. The laser is operated in the CW and Q-switched modes and the variation of output power at various arc lamp currents are noted for different Q-switch frequencies.

High power and high brightness CW Nd:YAG laser has its importance whenever high intensity and coherence are required. High output power in the TEM_{00} mode is obtained when a larger mode cross section inside the rod is used. This can be achieved by considering the laser rod as a thin, positive lens which is induced by the thermally generated refractive index gradient and stresses inside the crystal and is called thermal lens. The mode characteristics are therefore determined mainly by the dioptric power of thermal lens which is proportional to the pump power. Because of the large cross section of the mode inside the rod, any change in the dioptric power has a strong influence upon the diffraction losses of the mode. The fact that these losses are not constant makes it difficult to characterize the laser by analyzing its output behavior. The different parameters of the laser processing are studied so as to make sure that the cutting tool is very accurate. The central idea of stabilizing the TEM_{00} mode by a thermally induced lens is to design the resonator in such a way that the beam waist of the mode within the rod is a defined minimum ω_0 , at the chosen input power P^*_{in} . The beam diameter at the output coupler is measured using Beam profiler (Model Beam Scan,Photon Inc, USA) for different pump power. The beam diameter $(\frac{1}{e^2})$ of the laser beam is measured in the CW operation by changing the input pump power using beam profiler with its head placed just in front of the output coupler. The experiment is repeated for three different Nd doping concentrations and the variations are shown in Fig. 4 below.

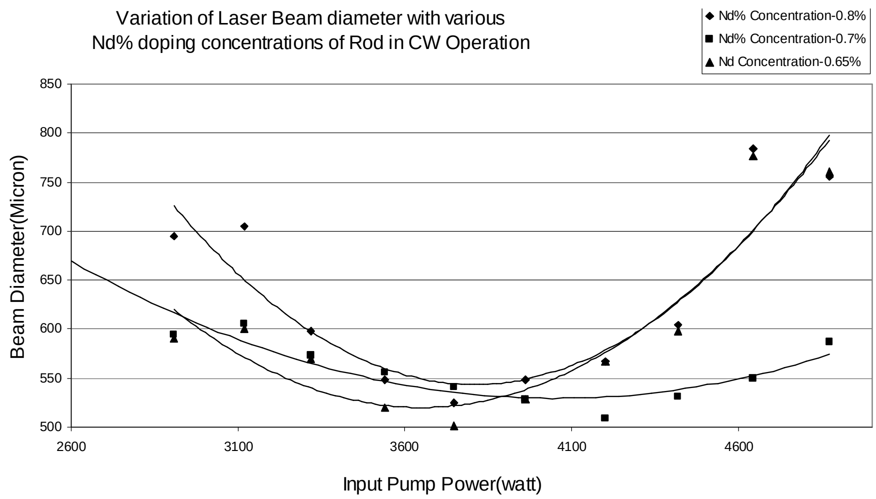


Fig. 2. Variation of Beam diameter of laser beam with input power at various Nd concentrations of active medium.

It is observed that the beam diameter is minimum for a particular pump power P_{in}* and it is varying with Nd doping concentration. The input power P_{in}* for which the beam diameter is minimum is calculated for different doping concentrations from the curves shown in Fig. 2 and are given in the Table 1. Also minimum beam waist for the three concentrations are calculated from Fig. 2.

Table 1. Variation of P_{in}* and w* for different Nd doping concentrations.

No	Parameter	Nd doping concentration (%)		
		0.8	0.7	0.65
1.	P_{in}*	3808.04	4055.401	3648.824
2	w*	543.7453	528.4647	519.5349

The input power P_{in}* for which the beam diameter is least for the three Nd doping concentrations are in the order

$$P^*_{in-0.7} > P^*_{in-0.8} > P^*_{in-0.65} \tag{1}$$

The minimum beam diameter w* for these concentrations are in the order

$$w^*_{0.65} < w^*_{0.7} < w^*_{0.8} \tag{2}$$

From these observations, it may be assumed that minimum beam diameter for the Nd:YAG laser decreases linearly with Nd concentration. This behavior can be explained using basic resonator theory. For a passive laser resonator, using ABCD law the matrix can be obtained as given below.

$$\begin{pmatrix} 1-\dfrac{L}{R_1} & L \\ \dfrac{-1}{R_1}-\dfrac{1}{R_2}+\dfrac{L}{R_1R_2} & 1-\dfrac{L}{R_2} \end{pmatrix} = \begin{pmatrix} g_1 & L \\ \dfrac{g_1g_2-1}{L} & g_2 \end{pmatrix} \tag{3}$$

where g_1 and g_2 are the stability parameters given by $g_1 = 1-\dfrac{L}{R_1}$ and $g_2 = 1-\dfrac{L}{R_2}$.

When an active medium is introduced between the two flat end mirrors($R_1 = R_2 = \infty$), the ABCD matrix changes as follows.

$$\begin{pmatrix} 1-\dfrac{L_2}{f_e} & L_1+L_2-\dfrac{L_1L_2}{f_e} \\ \dfrac{-1}{f_e} & 1-\dfrac{L_1}{f_e} \end{pmatrix} = \begin{pmatrix} g^*_1 & L_{eff} \\ \dfrac{-1}{f_e} & g^*_2 \end{pmatrix} \tag{4}$$

where $g_1^* = 1-\dfrac{L_2}{f_e}, g_2^* = 1-\dfrac{L_1}{f_e}$ and $L_{eff} = L_1+L_2-\dfrac{L_1L_2}{f_e}$.

Introducing an active element into the resonator, such as a laser crystal, in addition to altering the optical length of the cavity, will perturb the mode configuration, since the active material possesses a, saturable non uniform gain and exhibits thermal lensing and birefringence. In high-gain, giant –pulse lasers, gain saturation at the center of a TEM_{00} mode can lead to a flattening of the intensity profile [20,21]. Also, pump nonuniformities leading to a non uniform gain distribution across the beam will lead to non-Gaussian output intensity profiles. Theoretical and experimental investigations have shown that in solid state lasers that governing mechanisms which distort the mode structure in the resonator are the thermal effects of the laser rod. Optical pumping leads to a radial temperature gradient in the laser rod. As a result, in CW and high average power systems, the rod is acting like a positive thick lens of an effective focal length f_e which is inversely proportional to the pump power P_{in}. The theory necessary to analyse resonators that contain optical elements other than end mirrors has been developed by Kogelnik [22]. We will apply this theory to the case of a resonator containing an internal thin lens. To a first approaximation, this lens can be thought of as representing the thermal lensing introduced by the laser rod. The beam properties of resonators containing internal optical elements are described in terms of an equivalent resonator composed of only two mirrors. The thermal lens focal length f_e is inversely proportional to input pump power P_{in}. So

$$f_e = \frac{1}{\alpha P_{in}} \tag{5}$$

Hence

$$L_{eff} = L_1 + L_2 - L_1L_2\alpha P_{in} \tag{6}$$

In the present investigation, the TEM_{00} mode spot at one mirror can be expressed as a function of the resonator parameters as

$$w_1^{\,2} = \frac{\lambda\left(L_1 + L_2 - L_1 L_2 \alpha P_{in}\right)}{\pi}\left(\frac{g_2}{g_1(1-g_1 g_2)}\right)^{\frac{1}{2}} \tag{7}$$

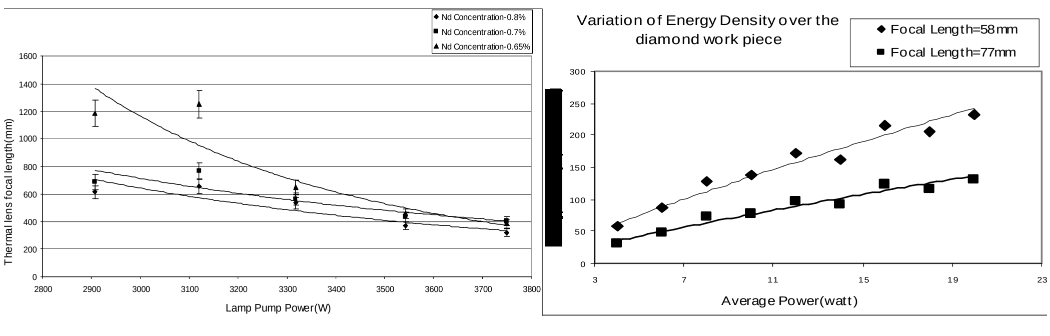
Let us consider the case of present investigation where two plane mirrors are used as end mirrors so that $R_1=R_2=\infty$ and a thin lens in the center ($L_1 = L_2 = \frac{L}{2}$), $g = g_1^* = g_2^* = 1 - \frac{L}{2 f_e}$ and

$$w_1^{\,2} = w_2^{\,2} = \left(\frac{\lambda L_{eff}}{\pi}\right)\left(1 - g^2\right)^{-\frac{1}{2}} \tag{8}$$

For $f_e=\infty$ the resonator configuration is plane-parallel for which the beam diameter w tends to infinity, for $f_e = \frac{L}{2}$ one can obtain the equivalent of confocal resonator where a finite value of beam diameter is obtained and for $f_e = \frac{L}{4}$ the resonator corresponds to a spherical configuration for which the beam diameter w again tends to become equal to infinity. This behavior is in agreement with that from Fig. 4 for three different values of Nd doping concentrations.

The mode size in the resonator will grow to infinity as the mirror separation approaches our times the focal length of the rod. In the presence of thermal lensing, the TEM_{00} mode volume is reduced by the focusing action of the rod [25] and by thermal aberrations of the Gaussian wave front[24].Thermally induced birefringence inside the crystal causes partial depolarization of the TEM_{00} mode [19]. The reduced value of P_{in}* obtained for the highest doped Nd concentration (0.8%) may be due to the heat deposition in the crystal caused by cross relaxation and up conversion proceses. This indicates that the thermal lensing level is higher for 0.7% crystal compared to the others. For 0.65% doped crystal normally the number of Nd^{3+} ions will be less compared to the other two as the dimensions of three crystals are the same. So the saturation level will be reached easily.

The variation of thermal lens focal length with lamp pump power at different Nd doping concentrations is plotted as shown in Fig. 3(a). The energy density at the work piece is calculated for two different values of focal length of focusing lens (58 mm and 77 mm) from the expanded beam diameter, beam quality factor (M^2 parameter) and the focal length of focusing lens used. The variation of energy density with average power was plotted and is shown in Figs. 3(b).



3(a) 3(b)

Fig. 3 (a). Variation of thermal lens focal length with pump power at different Nd concentrations of active medium (b)Variation of energy density with average power of the Q-switched laser at 8 KHz repetition rate.

It is observed that the thermal lens focal length is decreasing with increase in electrical pump power in all the three Nd doping concentrations. The thermal lens focal length is more for 0.65% doped crystal compared to the others. The focal length is decreasing drastically with input pump power in the case of 0.65% doped crystal where as the decrease is much more steady in the case of 0.7% and 0.8%.The energy density at the work piece is higher with the focusing lens of focal length 58 mm as the spot size is smaller compared to the other.

2.2 Optimization of laser processing of diamond

The laser is operated in the Q-Switched mode at a repetition rate of 4 KHz so that the output beam will be suitable for sawing the diamond sample. The thickness of diamond to be sawn and hence the angle of cut are determined by the software. The movement of CNC table is controlled by the signals sent by the software so that the material removal is layer by layer. Due to the finite size of the laser focal spot and the cone angle of the beam, it is not possible to saw through large diamonds simply traversing the beam back and forth over the same area. In order to overcome this difficulty, a benching process is adopted. Several benching traverses are made across the stone to produce an opening many times wider than the focal spot diameter. After the removal of the uppermost layer as mentioned above, the table moves upwards in the z- direction so that the next layer of diamond will be within the depth of focus (Raleigh limit) of focused laser beam. For the second layer the number of benching steps is reduced to obtain the aforesaid *"V"* cut.

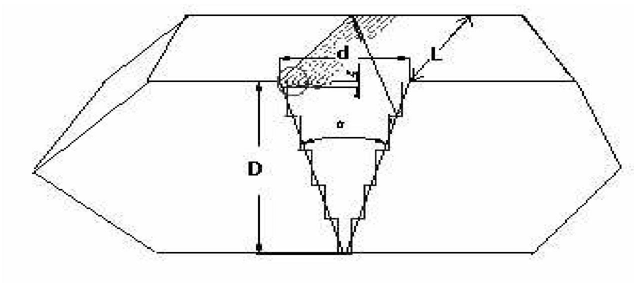
2.2.1 Analysis of weight loss and productivity

As mentioned before the diamonds are weighed before and after laser cutting. The opening angle(α) of the "V" shaped groove are gradually varied per diamond and corresponding weight loss were measured. As per the cutting profile shown in Fig. 4(a), the opening angle α is given by

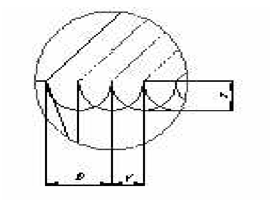
$$\alpha = 2\tan\left(\frac{d}{2D}\right) \tag{9}$$

where d is the width of opening and D is the depth of cutting. The aspect ratio of cutting is defined as ρ and is given by

$$\rho = \frac{D}{d} \tag{10}$$



4(a)



4(b)

Fig. 4(a). Geometry of the "V" shaped Groove made in the diamond stone (b) View of the ablation profile per pass of laser beam.

The back and forth movement of CNC table is in the Y-direction. The schematic sawing geometry is shown in Fig. 4. In the figure the cut angle seems to be very large, but in actual practice the angle will be very small of the order of milliradian. Some samples of natural diamonds are selected for the experiment. They are weighed before cutting and after cutting to find out the weight loss.

2.2.2 Weight loss parameter (W) and time parameter (τ)

A parameter called weight loss parameter W is defined and is given by

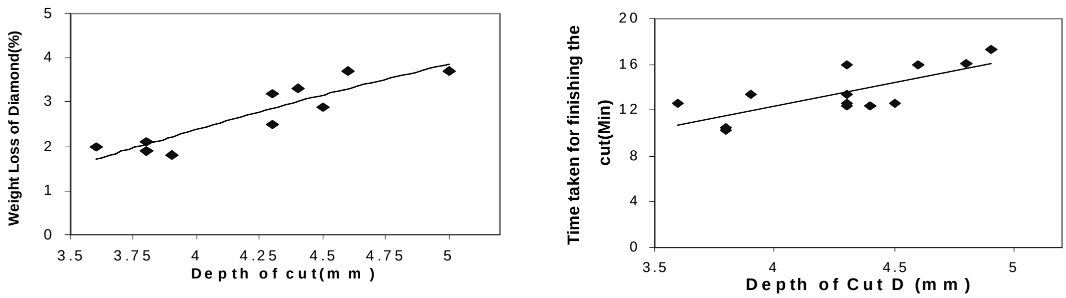
$$W = \tan\left(\frac{\alpha}{2}\right) \tag{11}$$

The variation of weight loss with opening angle is plotted and is shown in Fig. 5(a) below. The weight loss of diamond during cutting is found proportional to the weight loss parameter W. Another parameter called the time parameter is defined as

$$\tau = \frac{\tan\left(\frac{\alpha}{2}\right)}{y * z * v} \tag{12}$$

where L-The travel of benching process,y-width of channel made over diamond due to one single pass of laser beam,z-the thickness of material removed due to one single pass of laser beam, v-Velocity of travel in the Y-Direction.

The total cutting time is noted for various opening angle of cutting and the variation of processing time is plotted with opening angle. The graph is shown in Fig. 5(b).



5(a) 5(b)

Fig. 5. Variation of weight loss parameter of diamond during cutting(5a) and the time taken(5b) for cutting with depth of cutting.

The total cutting time and hence the productivity of diamond cutting is found proportional to the time parameter τ.

3. Results

The Q-Switched Nd:YAG laser system is showing very good performance in terms of peak to peak out put stability, minimal spot diameter, smaller divergence angle , higher output power in both CW and Q-Switched modes and good fundamental TEM_{00} mode quality. The optimum output coupling is found as 80%. The intrinsic slope efficiency and cavity losses are found out in CW and Q-Switched operations. The thermal lens focal length is calculated for different Nd concentrations of active medium. Thermal lens focal length is decreasing quadratically with pump power. The thermal lens focal length is more for crystal with Nd doping concentration 0.65% and minimum for crystal with 0.8%. There is an optimum value for the Nd concentration above which output power is decreased due to fluorescence quenching effects. The energy density at the diamond work piece is found out at two different focusing lenses. In both the cases it is showing a linear variation with laser output power. The weight loss analysis shows that the present system is showing smaller weight loss compared to conventional cutting systems. The variation of weight loss with opening angle is studied. The variation of processing time is plotted with opening angle is studied. No considerable micro-cracking breakage problem is noticed.

4. Discussion

From the observations, the main processes involved in the diamond cutting are illustrated in Fig. 6. The main steps involved are absorption of radiation, heating of diamond sample, melting and vaporization, ablation and material removal. In the initial stage the absorption of laser radiation by the diamond sample is taking place. The absorption process comprises of two parts. They are nonlinear optical absorption (multi photon absorption) and linear absorption. There are chances of multi-photon processes in the absorption of laser radiation by diamond because of its wide band gap .Thus multi-photon process are required for the excitation of electrons. As diamond has a band gap of 5.47 eV, 5-photon processes are needed at 1064 nm, 3-photon processes at 532 nm and 2-photon processes at 266 nm for initial excitation of electrons. It can be assumed that the absorption of energy by the free carriers that are produced in the initial stages of pulse plays an important role in the overall energy deposition. It means that even though nonlinear absorption across the band gap is necessary for the production of free carriers, later on the linear absorption of energy by the free carriers becomes dominant.

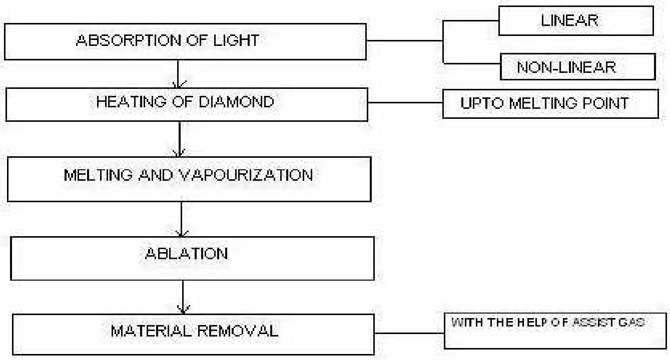


Fig. 6. Various processes involved in the laser cutting of diamond.

It is already mentioned that the cutting line is marked by black ink so as to enhance initial absorption which is not sufficient. In order to modify the diamond substrate, one need strong electronic excitations in diamond. In the nanosecond time regime, the laser ablation of diamond is disturbed with the undesirable thermal effects which drastically reduces the cutting efficiency. To our expectation, an important reason why laser pulses in the nanosecond range cause more undesirable material damage is the fact that there are processes competing with the laser excitation in the target region, namely the diffusion of hot carriers and heat conduction. These processes carry the energy and thus the damage far into the material while cooling down and de-exciting the focus area of the laser. Only if the laser pulse duration is shorter than the typical time scale of the competing processes (which is probably a few picoseconds), it is possible that ablation takes place via non-thermal processes. At the same time, shorter laser pulses also have higher power and thus, multi-photon absorption becomes more likely). From the experimental evidence we have seen, this seems to give much better results in terms of precision material processing.

Due to the absorption of laser radiation, the sample gets heated up. In this stage the main problem we encountered was the spreading of heat into unwanted zones inside diamond and hence the increased Heat Affected Zone (HAZ). We identified this as the main reason for breakage problem during cutting. The temporal characteristics of laser pulses were optimized to solve this problem to some extent.

5. Conclusions

Laser cutting of diamond materials (natural, polycrystalline and chemical vapour deposition) and other super-hard materials used for industrial applications is accomplished without micro-cracking or surface distortion using short nanosecond all-Solid State Lasers. This allows direct write micro-fabrication of features without extensive post-grinding and polishing stages. A very good diamond processing should possess the lowest possible breakage rate, good accuracy, good surface finishing and low weight loss. The main causes of breakage what we found are very high power settings without considering the highly sophisticated nature of gem stone, lack of peal pulse suppression of the Q-Switching of the laser, poor quality focusing system and poor operational techniques. The percentage of stress induced breakage is very less compared those due to the poor utilization of laser energy on cutting. In the latter case the stones are to be redesigned. The surface finish of the cut is mainly depending on many factors. The physical condition of optical components of laser and alignment of laser beam are the main issues. The efficiency of software used for cutting should be high. The power levels used should be well controlled for stone by stone. The efficiency of CNC table movement and the stability of laser power supply, laser cooling water temperature are also key factors which determine cutting efficiency. Finally the externally induced vibrations of laser will also adversely affect the performance of laser cutting system. If the sawn surface is flat, then it will be easier to remove the layer of graphite which is formed on the cut surface.

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