Original scientific papers UDK 621.375.82:620.179
doi: 10.7251/COMEN1202194D

MACHINING OF HARD-WORKABLE MATERIALS USING TWO LASER BEAMS

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Abstract: The paper gives an overview of the importance of modern materials in industry and problems regarding their machining. Materials such as: composites, hard metals, different types of ceramics and similar are hard to machine using conventional methods, because of their nature and mechanical properties. One of the ways to solve the machining problem for this type of material is by using a laser beam machining with two beams. In this process each laser beam makes a groove on the working area while the volume of the material lying between the crossover of two beams is eliminated. Theoretical discussion on thermal properties of materials which were subject to laser machining created a mathematical model which was subsequently compared with the experimental results.

Keywords: laser, laser beam, conductivity, reflection, mathematical model, laser beam density, heat of vaporisation.

1. INTRODUCTION

Requirements regarding the reliability and life cycle of the products impose necessity to develop new materials such as composites, hard metals, different types of ceramics and similar. Composite materials are made by combining two or more different materials. The starting raw materials have mutually different properties, while their combination gives a totally new material with unique, entirely new and different properties in comparison to the individual constituent materials. The aim is to upgrade structural, thermal, chemical or some other properties of individual materials. The components are not mutually mixed or dissolved, so that there are two or more clearly separate and distinct phases within the composite. One phase, called reinforcement, imparts strength and hardness. The other is referred to as a matrix or binder and it surrounds and supports fibers or fragments of the reinforcement materials. The composite constituents can be heterogeneous materials: non-metals, ceramics, metals, polymers. The properties of newly formed material depend on the properties of constituent materials, their concentration, distribution and binding. All composites are characterized by some common features which make them special and distinct from other materials: high strength and rigidity - they can be stronger than steel; low density and mass, resistance to corrosion and high temperatures, chemical inertness, possibility of machining and moulding into different shapes, resistance and permanence. Enhanced properties of composite materials make their wide application possible. Due to their nature, especially mechanical properties, these materials are very difficult to machine by traditional machining processes. The introduction of laser and its use in the machining process is exactly one of the machining methods that successfully solves the specified problem.

Machining of materials using laser beam is a process without contact, because there is no tool (laser beam is a tool), therefore there is no tool wear, cutting force, mechanical strokes or damage. Laser beam can successfully machine all materials with low light reflexion and low heat conductivity, regardless of their mechanical properties. This process should be analysed in the sense of optimisation and management, on the one hand, and mutual interaction of two laser beams, on the other hand. Presence of the other laser beam changes the groove shape and internal temperature distribution, so it is very important to take these facts into consideration when determining the machining conditions.

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2. CONDITIONS OF CONDUCTING THE EXPERIMENTS AND PROGRAM PREPARATION

Research with regards to the composite materials machining using laser beam was performed at the *Laboratory for Manufacturing and Productivity Massachusetts, Institute of Technology Cambridge USA*, as a part of the project "Optimization of the Material Machining Process Using Laser". The equipment and material of the above Institute were used during conducting of the experiment.

2.1. CO_2 laser with the following characteristics:

- output power 1500W (2x750W),
- power stability: ±2%,
- power adjustments: 200-1500W,
- wave-length 10.6μ,
- laser head: length 2.5 m; width: 0.52 m and height: 0.55 m,
- Laser focal point with diameter of 0.178 mm, which is subsequently generated using computing methods.

2.2. Appropriate gas:

- CO_2 - 1.2% of consumption 1.7 l/h,
- N_2 - 14.8% of consumption 21l/h,
- He - 8.4% of consumption 8.4 l/h,
- maximum pressure 8 bar, minimum pressure 7 bar,
- consumption of water 57-76 l/h and temperature 15 C.

2.3. Tested material:

- ceramics and
- composite materials whose characteristics are specified in Table 1.

Table 1. Composite materials

No.	Machined material	Specific heat (J/kg K)	Heat conductivity (W/m K)	Temperature of vaporization ^0C	Heat of vaporization (J/g)	Density (g/ cm^3)
1	Carbon/teflon	874	12.7625	1059	12057	2.2
2	Glass/teflon	909	0.5125	1082	9057	2.37
3	Glass /polyester	1025	0.6	1400	46000	1.9
4	AL203	850	3.3	2072	4150	2.8

Maximum five passings were carried out during testing.

3. THEORETICAL ANALYSIS OF THE PROCESS

A detailed analysis of a groove creation process using laser beam was presented in the previous papers [1,8,13], and, due to the space limitation, it will not be considered in this paper in detail. We analyzed the creation of only one groove by using one laser beam (Figure 1). Within this analysis only one small particle was considered on the groove surface created using laser at angle θ to x axis and angle ϕ to y axis.

Based on that analysis, the energy expression can be defined, as follows:

$$aJ(dx.dy) = -k\left[\frac{dxdy}{\cos\theta\cos\phi}\right]\left[\frac{\partial T}{\partial n}\right]_{n=0} + qLV(dxdy)tg\theta \tag{1}$$

where:

a − is an absorption coefficient
J − is a laser beam intensity
k − is a heat conductivity coefficient
T − is a temperature of vaporisation
n − is a unit vector
q − is a laser beam density
L −is a latent heat of vaporisation
ϕ − an angle to y axis
θ − an angle to x axis
V − velocity of laser beam passing.

Based on the energy analysis, according to Figure 1, a few assumptions were made:

a) Laser beam has a Gaussian distribution [1]:

$$J = \frac{P}{a^2}\exp\left[-\frac{x^2+y^2}{d^2}\right] \tag{2}$$

where:

δ − is a heat penetration depth,
d − is a laser beam diameter,
P − is a laser beam power.

b) Conductivity within the workpiece of machining is normal to the groove surface, so that the temperature distribution expression will be as follows:

$$T = T_s\left[1-\frac{n}{\delta^2}\right]^2 \quad (3)$$

c) Laser beam reflection onto the groove surface is considered as the energy loss,

d) Vaporisation or plasma development are disregarded,

e) Melted material is removed by gas immediately during the operation, so that the effects of molten layer are disregarded.

A temperature gradient at the groove surface [5] can be calculated in the following way:

$$\left[\frac{\partial T}{\partial n}\right]_{n=0} = 2T_s\left[1-\frac{d}{\delta}\right]_{n=0}\left[1-\frac{1}{\delta}\right] = \frac{2T_s}{\delta} \quad (4)$$

Replacement of this relation by the expression (1) results in:

$$aJ = \frac{2kT_s}{\delta\cos\theta\cos\phi} + \delta\cdot V\cdot L\cdot tg\theta \quad (5)$$

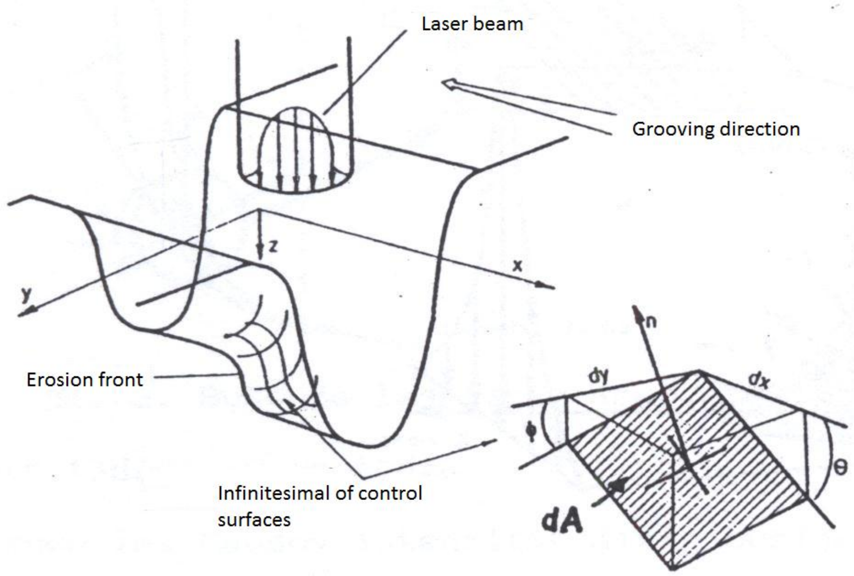


Figure 1. Creation of a groove using one laser beam

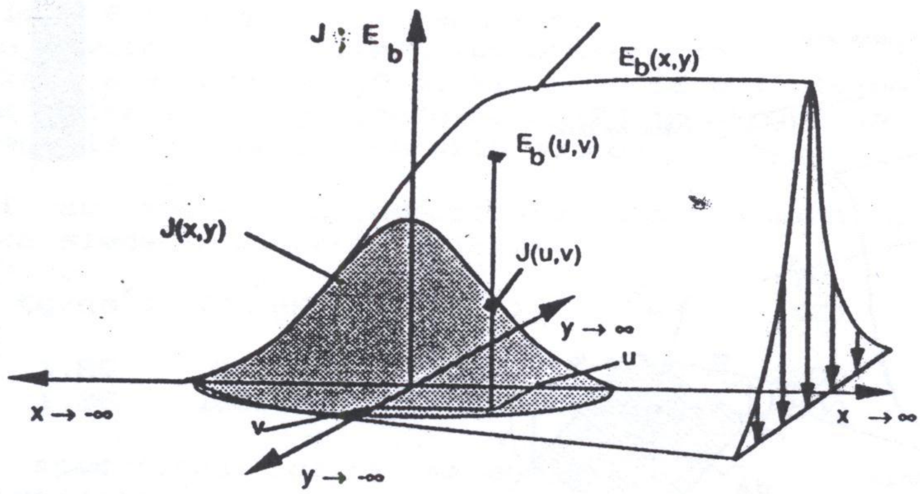


Figure 2. Laser beam intensity and energy distribution

Relation between heat conductivity within the workpiece and heat transmission occurring due to the heat source movement [7] can be obtained applying the heat transmission differential equation:

$$\frac{V}{a}\cdot\frac{\partial T}{\partial x} = \nabla^2 T = \frac{\Delta T}{\partial n^2} \quad (6)$$

Likewise, the temperature gradient can be expressed in the following form:

$$\left[\frac{\partial T}{\partial x}\right]_{n=0} = \left[\frac{\partial T}{\partial x}\right]_{n=0} \sin\theta \quad (7)$$

Solving the energy equation (1) on the groove surface we obtain the following results:

$$\frac{V}{a}\cdot\frac{2T_s}{\delta}\cdot\sin\theta = \frac{2T_s}{\delta^2} \quad (8)$$

The heat penetration depth δ is obtained using the following expression:

$$\delta = \frac{a}{V\cdot\sin\theta} \quad (9)$$

$$a\cdot J = \delta\cdot V\cdot tg\theta(2C_p\cdot T_s\cdot\sec\phi + L) \quad (10)$$

where:

Cp − is specific heat of the working piece.

tgθ can be calculated using the equation (10):

$$tg\theta = \frac{\frac{aP}{d^2}\exp-\left[\frac{x^2+y^2}{d^2}\right]}{(\delta\cdot V(2C_pT_s\cdot\sec\phi + L)} \quad (11)$$

Integration of expression for the groove depth ranging from -∞ to +x results in:

$$s(x,y) = \int_{-\infty}^{x} ds + S_t \quad (12)$$

where:

St − is previous depth of groove,

ds − measured depth of groove during the laser beam penetration.

Now, an integral relation for the groove depth takes the following form:

$$s(x,y) = \int_{-\infty}^{x} \frac{\frac{aP}{d^2}\exp-\left[-\frac{x^2+y^2}{d^2}\right]}{\delta\cdot V\cdot(2C_p\cdot T_s\cdot\sec\phi + L)}dx + S_t \quad (13)$$

Temperature of the groove surface Ts and the inclination ϕ along y – direction are functions of x and y. Generally, solution for the groove shape requires determination of ϕ and Ts. The central change of the groove depth can be calculated when y and ϕ equal to zero.

Increase of the groove depth value can be computed using the following model [8]:

$$\Delta D = \frac{a\cdot\pi^{1/2}\cdot P}{\delta\cdot V\cdot d(C_p\cdot T_s + L)} = \frac{2aP}{\pi^{1/2}\cdot q\cdot V\cdot d\left[C_p(T_s - T_o) + L\right]} \quad (14)$$

or:

$$\log(D/d) = \log\frac{P\lambda}{V\cdot d} + \log\frac{2a}{\pi^{1/2}\cdot q\cdot V\cdot d\left[C_p(T_s - T_o) + L\right]} \quad (15)$$

where:

λ..- is a number of laser beam passings,

D- is a depth of the laser beam penetration,

or:

$$\log(D/d) = \log(ED/d) + \log\left[a\cdot\pi^{1/2}\cdot d / q(2C_pT_s + L)\right] \quad (16)$$

Maximum groove depth can be determined using this analytical process without a repetition of numerical methods.

4. EXPERIMENTAL RESULTS

Power levels of 400 and 500W, as well as the laser beam passing velocity (V = 0,254; 0,508; 0.762; 1.27; and 1.905 cm/sec) were applied during testing. Machining of composite materials was performed in axial and radial directions (Figure 3); the results of the laser beam penetration depth under the same conditions are given in Figures 6a and 6b.

Upon the completion of the experiments, the groove depth and width were measured. However, the measurement results are not shown due to the space limitation, but only used for energy density calculation and graphic review of results.

Energy density can be determined based on the following equation:

$$ED = \frac{P\lambda}{V\cdot d}$$

where:

ED − is energy density,

λ − is a number of the laser beam passings,

V− is velocity of the laser beam passing.

Calculated values of relations ED/d and D/d are presented in Figures 4 and 5 for each material (carbon/teflon, glass/teflon, glass/polyester, Al 2O3) tested in the experiment. The same figures show both theoretical and experimental results, as well as their comparison.

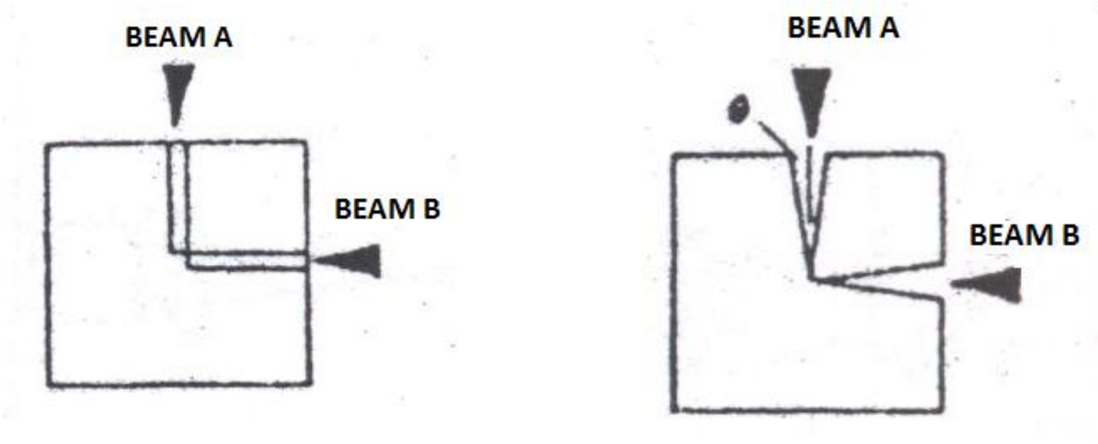
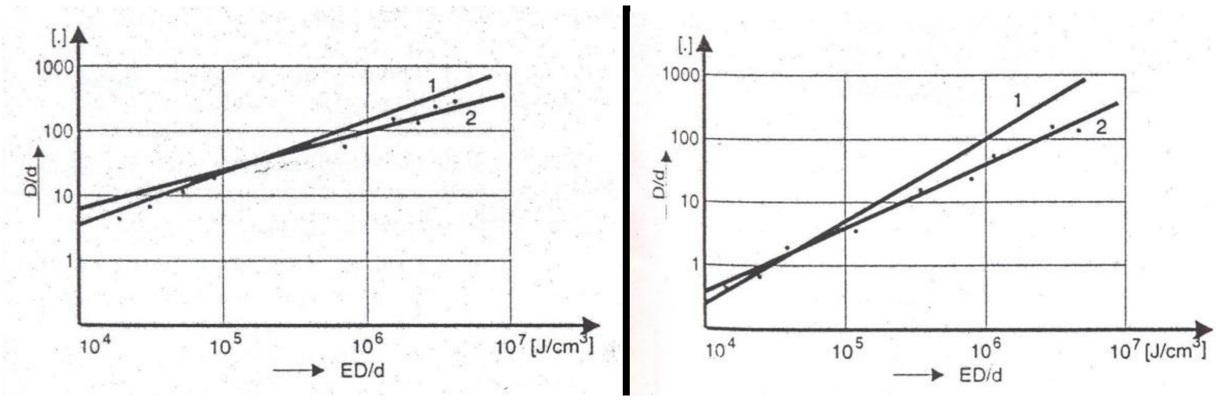
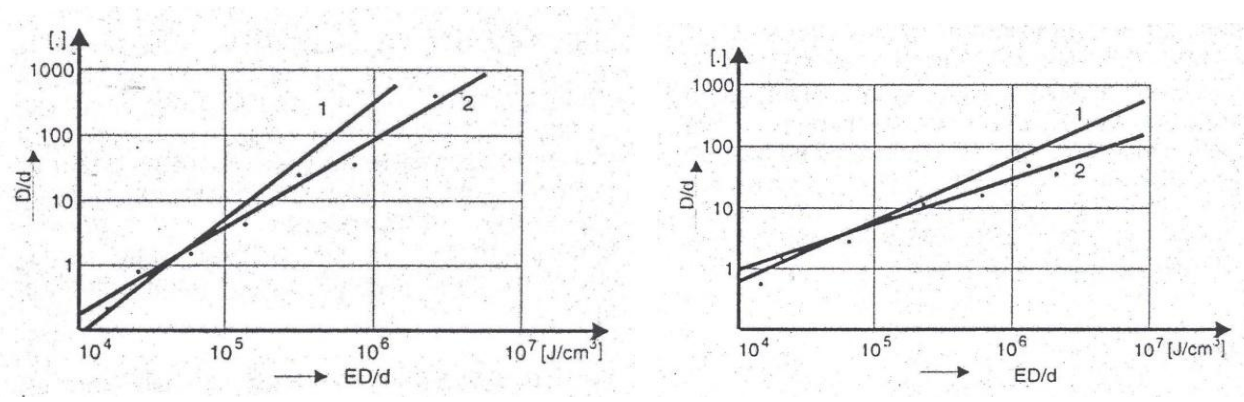


Figure 3. Machining using two laser beams



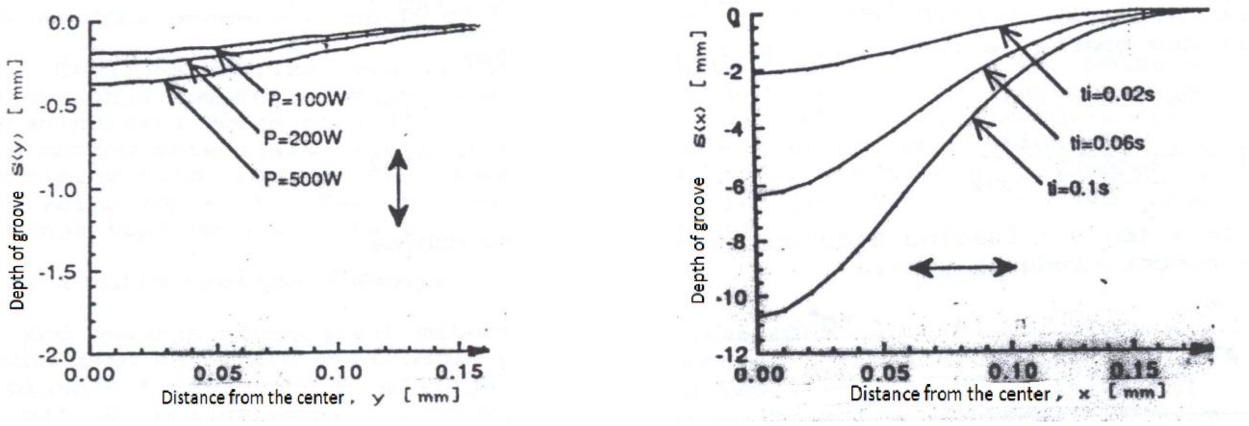
a) *carbon/teflon* b) glass/teflon

Figure 4. Comparison of computing (1) and experimental (2) results for carbon/teflon (4a) and glass/teflon (4b)



c) glass/polyester d) Al2O3

Figure 5. Comparison of computing (1) and experimental (2) results for glass/polyester (5c) and Al 2O3 (5d)



a b

Figure 6. Depth of the laser beam penetration: a) axial to the fibres; b) radial to the fibres

5. ANALYSIS OF OBTAINED RESULTS AND CONCLUSION

Based on the experimental results obtained, as well as on theoretical knowledge and the mathematical models gained for hard-workable materials subjected to experiment, the following can be concluded:

1. 3D machining of materials using two laser beams basically represents a creation of the groove by each laser beam, but the volume of eliminated material is considerably greater than when it is done by one laser beam, because, except of melted volume of material, the laser beam significantly eliminates greater volume of the material lying between the crossover of two laser beams (Figure 3). When machining the material using two laser beams, mutual interaction of laser beams must be taken into consideration, which is obviously reflected in the groove creation accuracy. Such interaction is shown in zoomed view in Figure 3.

2. Machining of composite and ceramic materials using laser beam does not represent any difficulty, which is also confirmed by obtained results showed in Figures 4 and 5. It implies that the statement given in the introduction of this paper is correct indicating that the laser beam can successfully machine all materials regardless of their characteristics and mechanical properties. The fact is also that there are difficulties with the materials having greater ability of heat conductivity and reflection, but this problem too is solved with appropriate preparations.

3. Experimental results are compared with the theoretical models and showed in Figures 4 and 5. Deviations between theoretical models and experimental results are obvious, but they are within the standard allowed limits. Slightly greater deviations are particularly noticeable in the area of deeper penetration of laser beam into materials, i.e. with deeper depth and higher relation of ED/d, as well as with materials glass/polyester. These deviations are greater with materials glass/polyester than with other materials, and they can be explained by the laser beam increased reflection in comparison to other materials.

4. There is a considerable difference in the laser beam depth depending on whether the machining is performed axially or radially to the material fibres. Such a difference is evident in Figure 6 and explained by higher heat conductivity when laser beam machining is performed axially to the material fibres.

Notwithstanding insignificant deviations existing between experimental and computing data, it can be said with certainty that the composite materials can be very successfully machined with the use of laser.

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ОБРАДА ТЕШКО ОБРАДЉИВИХ МАТЕРИЈАЛА СА ДВА ЛАСЕРСКА СНОПА

Сажетак: у раду је дат кратак преглед значаја савремених материјала у индустрији и проблема са њиховом обрадом. Материјали као што су: композити, тврди метали, разне врсте керамике и слично, тешко се обрађују конвенционалним поступцима, с обзиром на њихов карактер и механичке особине. Један од начина рјешавања проблематике обраде за ову врсту материјала је обрада помоћу ласера са два ласерска снопа. У овом процесу сваки ласерски сноп прави жљеб на радној површини и волумен материјала који се нашао између пресјека два ласерска снопа се отклања. Теоретским разматрањем термичких својстава материјала који су били подвргнути ласерској обраді направљен је математички модел који је касније упоређен са експерименталним резултатима.

Кључне ријечи: ласер, ласерски сноп, кондуктивитет, рефлексија, математички модел, густина ласерског снопа, топлота испаравања.