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LASER HEATING OF CONSTRUCTION MATERIALS

Damian Przestacki[1], Tadeusz Chwalczuk[1], Aneta Bartkowska[1], Grigor Stambolov[2],

[1] Poznan University of Technology, Institute of Mechanical Technology, Poland
[2] Technical University - Sofia, Faculty of Industrial Technology, Bulgaria.

Abstract: *This paper analyzes laser heating processes and their effects on the material thermal response. The radiation-materials interactions are treated as a coupled process as heating of the metal lattice through electron-phonon collisions. Pulse duration, heating intensity and time of heating are key parameters of manufacturing process. The construction materials like cemented carbides, ceramics, metal matrix composites are increasingly attractive because of their superior combination of properties such as high strength, hardness and fracture toughness. These materials are finding potential applications in the manufacture of transport components such as wheel/rail systems, electrical. One of the ways to improve the wear performance of machine parts is application of sintered carbides layer by laser cladding method. However, these materials belong to the group of difficult to cut materials. Innovative machining solutions are required to reduce the cost of production of these materials.*
The paper under discussion focuses on the analysis of the impact of the laser beam on various construction materials and shows a current trends in laser heating.

Keywords: *laser heating, temperature, construction materials*

1. Introduction

Manufacturing of new elements that are made of hard technical ceramics, cemented carbides caused the necessity, after sintering process, of their work surfaces precise shaping. Such shaping is usually applied in the form of machining [6]. Because of the great hardness of Al_2O_3, Si_3N_4 and ZrO_2+WC ceramics, process of their machining is not so efficient and is expensive one [7]. The recent trend is the machining of hard technical ceramics that is aided by the laser heating of the removed layer [2-4]. It enables to increase the machining efficiency and to improve the economical coefficients of the process.

Setting conditions of laser heating for the layer that is to be removed, is the essential problem both scientific and practical one. Solving this problem enables to apply new machining technology of the difficult to cut materials.

Maximum temperature on the surface of the laser heated material, can be determined as [5,7]:

$$T(t) = \frac{\eta P}{\Pi r_p^{2} \lambda} \times (4at)^{0,5} \tag{1}$$

where:

P - laser beam power,

r_p - radius of laser beam on the heated surface

t - laser beam action time

λ - coefficient of thermal conductivity

a - coefficient of temperature conductivity (thermal diffusivity)

η - absorption coefficient of laser radiation by heated material

The basic problem that occurs while applying the temperature evaluation dependencies, is caused by the fact that thermal properties and material absorptivity essentially depend on material temperature as well as on the heated surface state. It is also hard to use the remote measuring method for surface temperature by means of the infrared sensors. Such measuring needs the calibration of the whole measuring system for each investigated surface in order to determine the emissivity coefficient that depends on the heated material properties as well as on the heated surface state.

2. The range and methodology of investigations

In order to determine the laser heating conditions for ceramics, there have been investigated the materials, presented in Table 1.

Table 1 Characteristic of the heated ceramic samples

Kind of ceramics	Hardness $HV_{0,5}$	Grain size [μm]
Al_2O_3 (99,7%)	1975±33	2÷5
Si_3N_4	1809±40	2÷4
composite ZrO_2+WC	~ 1400	–

Investigations have been divided into two stages: calibration of temperature measuring system and performing of basic investigations in order to determine the laser heating conditions of the surfaces up to temperature T that is applied in machining.

Basic investigations of heating the ceramic samples have been carried on the laser stand. The stand is composed of the technological laser CO_2 (TFL 2600t made by TRUMPF) that is connected with turning machine TUM35D1 with stepless spindle rotation control. The stand has been equipped with the path of the remote temperature measuring, (Raytek), based on the principle of the infrared detection radiation, additionally equipped with computer result registration. In order to determine the emissivity coefficient ε for investigated materials, the calibration of the contactless thermometer has been performed according to the methodology presented in [1].

Investigated ceramics materials have been heated (Fig.2) while rotation with revolution speed n that has been measured as the linear velocity v_l of laser beam movement along the heated surface or while simultaneous rotation (n) and straight line movement along the work piece axis with velocity of v_f, that has been measured as the feed rate f (mm/rev). While heating of the investigated pieces the active (on line) measurements as well as registration of the temperatures have been carried on.

Basing on the performed investigations mathematical models of the investigated object has been determined in the form:

$$T = a \ln t + b \tag{2}$$

where:

T - temperature of the heated surface [°C]

t - heating time [s], [min]

On top of that the square of the correlation coefficient R^2 has been also determined.

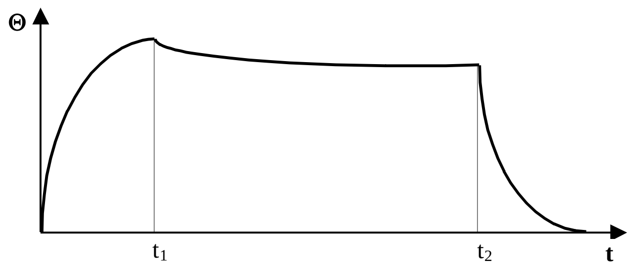

Fig. 1 Particular phases of the laser heating of the Si_3N_4 ceramics

The ceramics softening, by means of laser heating, is performed in the time range $0 < t \le t_1$ (Fig.1). As soon as the machining starts, (time t_1 from the heating start) the temperature decrease of the machined surface is observed due to the separation of the heated chip. After machining (time $t \ge t_2$ - Fig.1) and disconnecting the laser heating the monotonic decrease of the temperature of the machined surface has been observed.

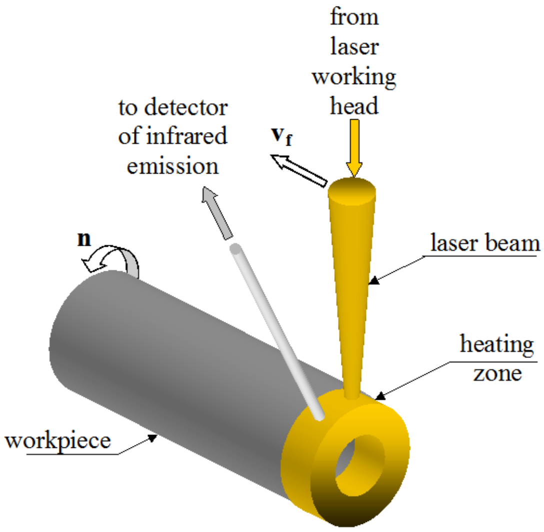

Fig. 2 Schematic process of material laser heating and remote control of measuring the surface temperature

Fig. 3 shows the schematic of laser assisted machining setup used during heating the metal matrix composites. Surface temperatures were measured with a two RAYTEK pirometers (model:MA2SC and S5XLT). One of these measured temperatures in *A* area [Fig.31] and the second in *B* area [Fig.3] at the same time. Emission was set in the software to a value of ε=0.3 based upon calibration tests primary maked.

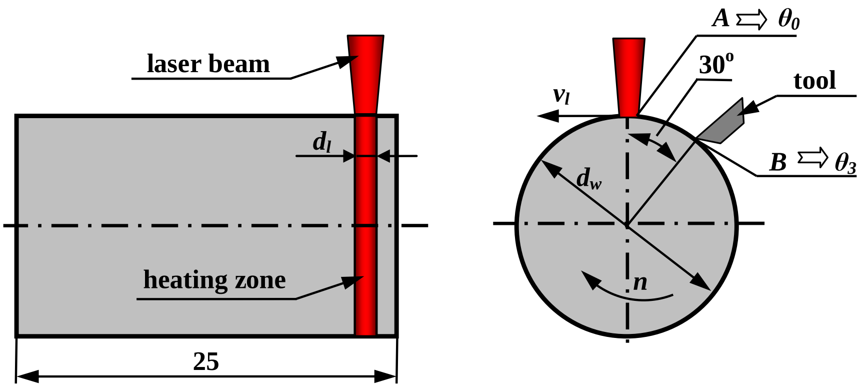

Fig. 3 Schematic of experimental set-up for metal matrix composite material. Designations: *A* - heating area by laser beam, *B* – zone of machining, θ_0, θ_3 - areas of temperature measurement, d_w- workpiece diameter, d_l - laser beam diameter

The constant parameters for metal matrix composites were: cutting speed (v_c=107m/min), depth of cut (a_p=0,1mm), feed (f=0,04mm/rev), emissivity (ε=0,3), cutting time (t=0,73min) and workpiece diameter (d_w=38mm). Several others parameters were variables: laser power (P=0.26÷2.34 kW), laser beam diameter (d_l =2÷4mm)

3. Investigation results and their analysis

Investigation results of heating the Si_3N_4 ceramics for various density of the laser radiation power while rotation of the workpiece and v_f = 0 have been presented in Fig.4. Increasing of the power density of the laser radiation makes significant change in the intensity of the investigated surface temperature as well as the increase of the maximal temperature that is achieved on the ceramics surface. The applied mathematical models describe the *T (t)* dependencies with great coefficient of correlation that enables their practical use.

Investigations concerning the heating of ceramics Al_2O_3 proved that so called “white ceramics” is low resistant on the rapid temperature changes. Its slow heating and slow cooling makes significant increase of the process time and therefore it becomes ineffective as auxiliary machining process.

Heating for constant conditions *P*, *q* enables to shorten time of the process, but due to the free cooling, the workpieces made of white ceramics cracked close to the self-centring chuck that means at the place when intensive heat reception occurred.

At the second investigation stage, investigation results have been presented in Fig.5, the laser beam moved in relation of the heated surface on the helical line with the velocities equivalent to the conditions of turning the hard technical ceramics.

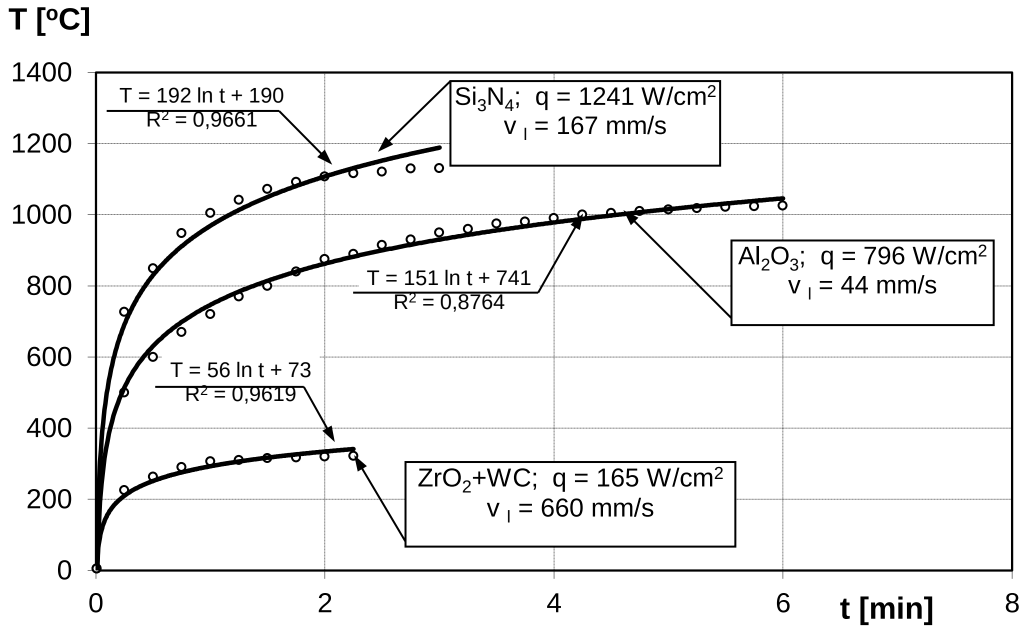

Fig. 4 Temperature *T* of surface sleeves made of Si_3N_4, Al_2O_3, ZrO_2+WC vs. time *t* of heating by means of laser beam with various power density *q*

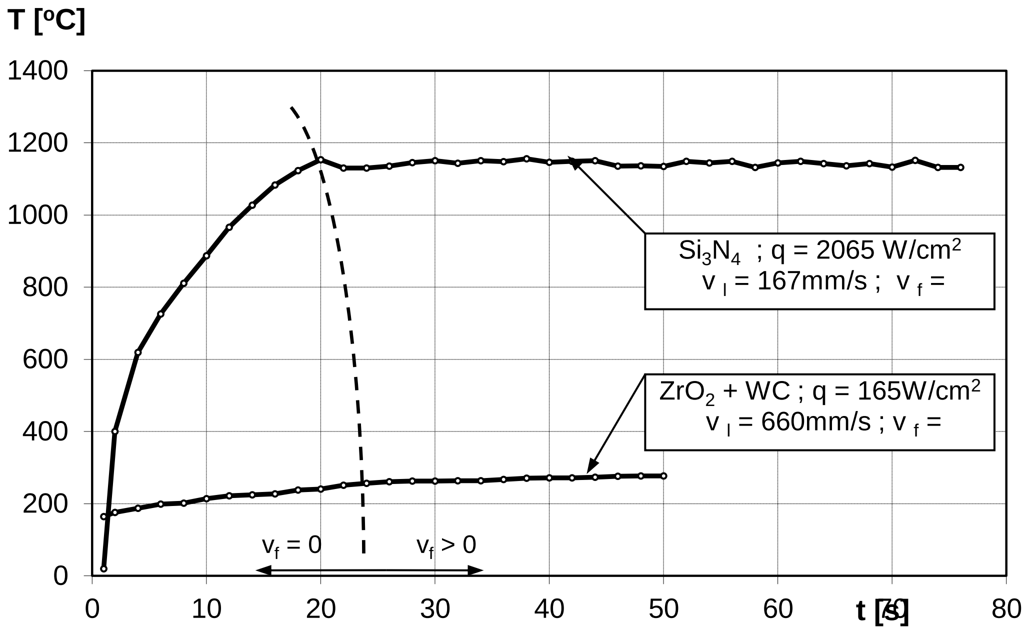

Fig. 5 Surface temperature of Si_3N_4, ZrO_2+WC ceramics while laser heating of the workpiece along the helical line with various power density *q*

As it has been presented in Fig.5, at the initial heating phase, while rotation movement of the workpiece (v_f = 0), the intensive increase of the surface temperature occurs. After switching the feed movement on and when the surface starts to be heated along the helical line the temperature of the ceramics workpieces gets stable and it depends on the density of the laser radiation.

Turning with cutting speed $v_c = 10$ m/min can be heated with constant laser beam power. Speed of laser beam motion relative to workpiece is relatively low in feed as well as circumferential direction ($v_f = f \cdot n \approx 10$mm/min) what enable constant and desirable temperature of cut, despite low thermal conductivity of turned ceramics (Fig. 6).

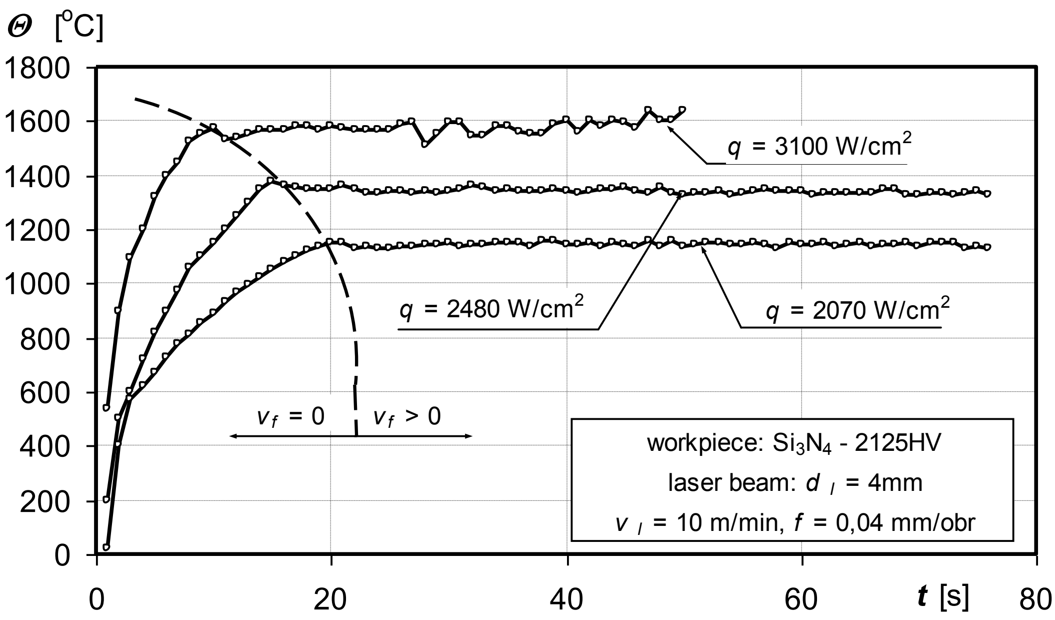

Fig. 6 Surface temperature of Si_3N_4 ceramics while laser heating of the workpiece along the helical line with various power density q

Increasing of removal rate by increasing of cutting speed and feedrate requires applying of increasing power of laser beam during cutting in order to obtain constant temperature of cut, because of low conductivity of ceramics (Fig. 7).

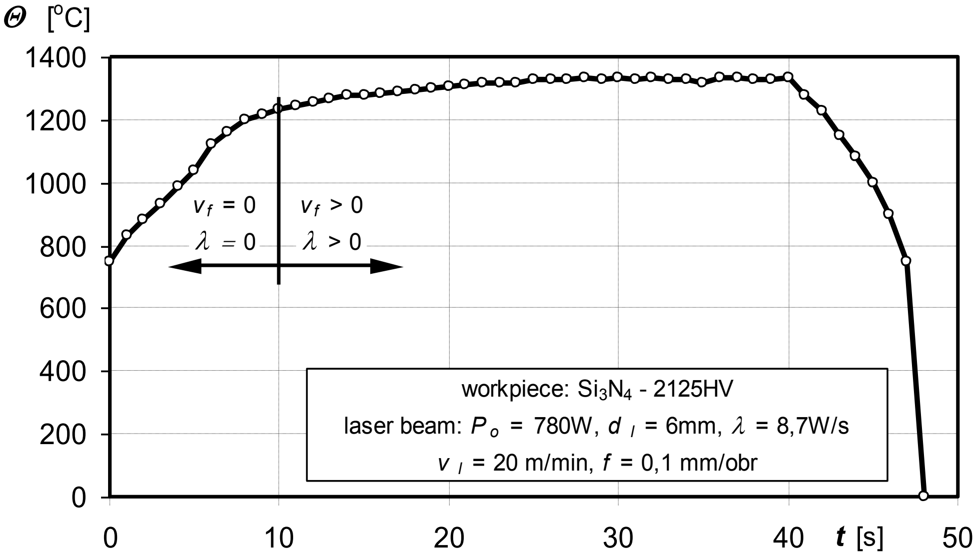

Fig. 7 Surface temperature of Si_3N_4 ceramics while laser heating of the workpiece

In Fig. 8 the effect of the laser beam diameter and laser power on the temperatures in *A* and *B* areas are shown. It was noticed that the temperature (θ_0) in *A* zone (Fig.8a) insignificant increases with increasing power of laser beam. Increase laser power more than three times causes small increasing temperature about 200 ^oC. In the case of the temperature (θ_3) in *B* area (Fig.8b) increases power of laser approximately about 1kW had distinct effect on increased temperature in this area. On the other hand increasing power of laser beam above 1 kW practically didn't change temperature (θ_3) in *B* area. It can be bring out of appearance plasma in area heated by laser beam which in this conditions intensively absorbs energy of laser radiation.

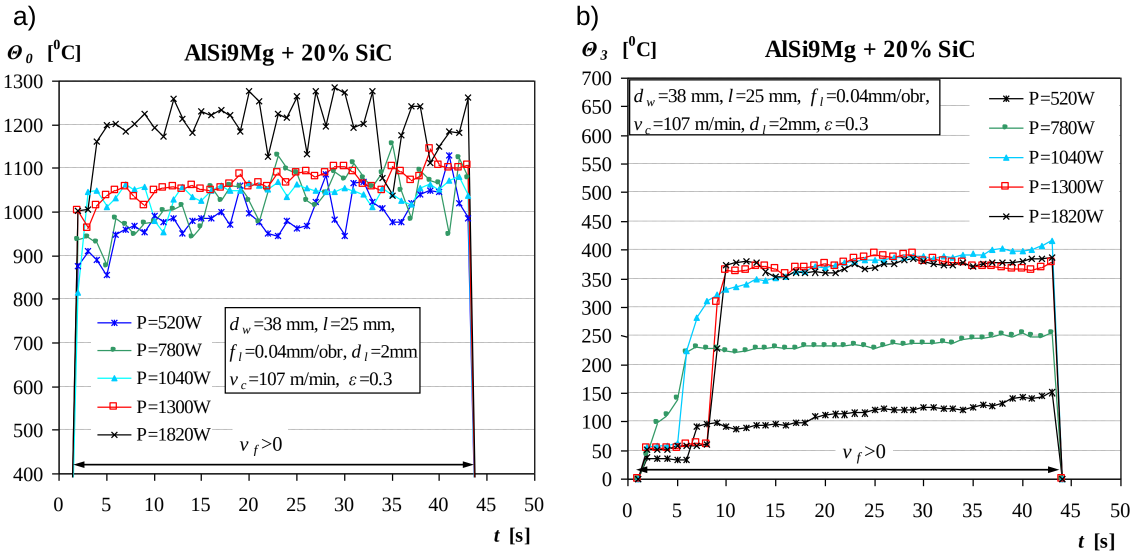

Fig. 8 Comparison of measured temperatures with different power of laser beam, a) measured from θ_0 area, b) measured from θ_3 area

4. Conclusions

The presented results of own investigations concerning the heating of ceramics Al_2O_3 prove, that molecular laser CO_2 due to the laser radiation wave length λ = 10,6μm, causes the cracking the Al_2O_3 material because of the small radiation absorption and occurring great temperature gradients. As it has been stated in [4], laser machining of the Al_2O_3 ceramics is possible but the lasers with the smaller length of the laser radiation should be applied $\lambda \leq$ 1,06μm.

While laser heating of Si_3N_4 ceramics as well as oxide-carbide composite (ZrO_2 + WC), cracking of the machined work pieces has not occurred independently on power density of laser radiation and cooling system after heating. As it was proved by investigation results, it is quite possible to reach certain stable temperature of the machined workpieces by controlling the parameters of the laser beam in kinematics conditions equivalent to machining by turning.

Laser- assisted machining is very effective method (in low range value to 1kW) of laser power) in the machining of SiCp/Al composite.

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