LASER BEAM INTERACTION WITH MATERIAL SURFACE

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The article describes the interaction of a laser beam with material surface, based on the oscillation of atoms in the crystal lattice, supposing that the oscillation amplitude is proportional to the temperature of the material. The principle of material removal using a laser beam is presented, along with its mathematical expression. The article also introduces a theory of laser beam interaction with material which is based on the principle of changing internal energy of the lattice. The research has been carried out for machining of pure substances using a diode-pumped, solid-state Nd:YAG laser with a mean power of 50 W.

Keywords
Laser, crystal lattice, atomic oscillation, material temperature, internal energy of crystal lattice

1. Introduction

In the literature, the interaction of a laser beam with the machined material is generally described with differential equations based on the knowledge of heat transfer. Our research focuses on a different aspect. Our idea of laser beam interaction with material surface is based on modern physics:

a) The beam of light emitted by a laser is a set of highly organised photons impacting the surface of the machined material. According to physics, a photon has its energy and mass and propagates through space at the speed of light. If a photon has the above-mentioned properties, it also has a capacity to exert pressure on the surface of materials. The energy of a photon is transferred in quanta. The quantum of energy of electromagnetic radiation grows with growing wave frequency, i. e. with shortening radiation wavelength;
b) The workpiece material is composed of atoms which, in metals, are organised in a crystal lattice. In metals atoms are characterised by their mass, crystal lattice bonds, movement and lattice energy;
c) The magnitude of the atomic oscillation amplitude within a crystal lattice is directly proportional to the temperature of the material.

Based on this knowledge, we have proposed a theory of interaction between photons and atoms as an oscillation process. Our considerations are the result of conducted experiments (see RCMT research reports mentioned in paragraph References) and their aim was to establish a method for evaluation of materiál machinability using a laser beam.

The proposed theory describing material removal (interaction) with a laser beam is based on determining the resistance of the crystal lattice of the machined material to deformation by impacting photons. Oscillation is due to the capacity of photons to make an atom oscillate to such a degree that it exceeds the maximum amplitude where it is still bonded to other atoms in the lattice. Another way of interaction described, based on atomic oscillation, uses current physical knowledge of crystal lattice internal energy.

Note: A part of the laser beam energy impacting the surface of a material is used to increase the energy of electrons on the surface of the material. Some of the electrons are thus released, ions are formed and plasma is created as an accompanying phenomenon of laser machining of metals.

2. A Theory of Laser Beam Interaction with Material Surface Based on Atom Oscillation

2.1 Introduction

In a lattice atoms oscillate around their middle position, with an amplitude corresponding to the temperature of the material. The higher the temperature, the greater the oscillation amplitude. At absolute zero, i.e. at T_0 = 0 K oscillation would stop, and the amplitude would therefore be zero. At evaporation temperature the amplitude of atom oscillation reaches its maximum, as this is the temperature at which atoms are released (evaporated) from the lattice, and material is thus removed.

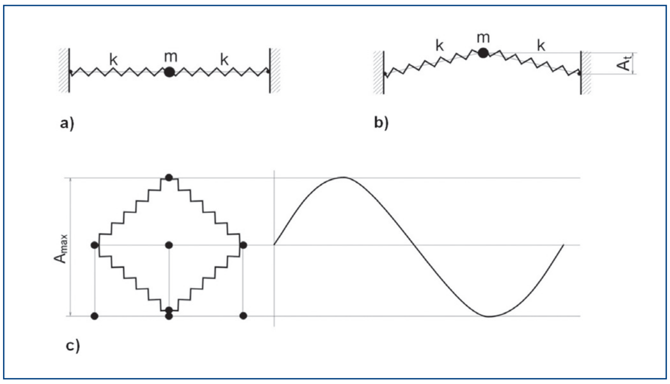

Figure 1. *The principle of atomic oscillation in the crystal lattice*

Conclusion: the amount of material removal depends on the capacity of the lattice to maintain the atom in a given arrangement. The magnitude of atomic oscillation in the lattice corresponds to a particular temperature. The amplitude of oscillation (i.e. its magnitude) depends on the force with which atoms interact in the lattice, i.e. on their arrangement, as well as on their mass.

The principle of micromilling: material is removed with a laser beam transferring the energy of a photon to an atom, thus releasing the atom from its lattice (‚evaporating' the atom).

The principle of cutting: by acting on the surface of material a laser beam melts the material: the forces in the lattice are only disrupted to such an extent that the metal becomes liquid, and the atoms cluster into molecules which are again bonded by forces. In practice, material is removed using auxiliary gas which blows the molten material away from the point of impact of the laser beam. The coherence of the crystal lattice is disrupted in this case as well; the forces acting on the atoms, however, can be smaller, and the amplitude corresponds to the melting temperature of the machined material.

Removal of materials with a low melting point (tin and lead): the factors which probably play an important part here include the bonding forces acting during transition from liquid to gas, and the difference between melting temperature and evaporation temperature. For example, micromilling of lead and tin with a laser beam is easy, starting from the speed of 60 mm*s^{-1}, i.e. with a smaller amount of energy supplied for the evaporation of atoms.

2.2 The Principle of Oscillation

For oscillation magnitude the following conditions are considered:

a) At absolute zero atoms do not oscillate;
b) With growing temperature the magnitude of atomic oscillation (amplitude) within the lattice grows as well. For the first approxi-

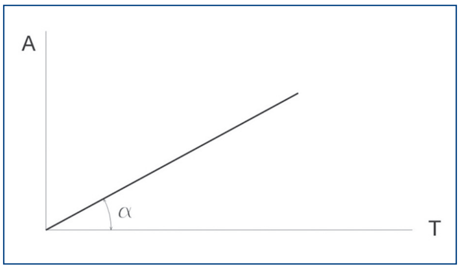

Figure 2. *The dependency of amplitude on temperature*

mation we suppose a linear dependency A = f(T) = kT, where k is the slope of the line (Fig. 2);

c) At any higher temperature atoms oscillate with an amplitude corresponding to the temperature. This is why melting temperature corresponds to temperature T_t and amplitude A_t, and evaporation temperature corresponds to temperature T_v and amplitude A_v. For the influence of evaporation temperature on atomic oscillation corresponding to the temperature of the sample, see Fig. 3;

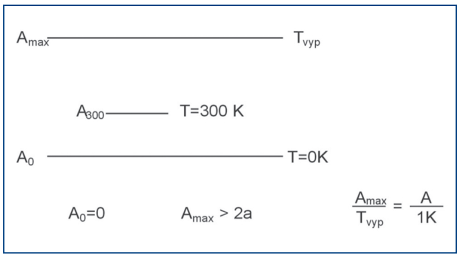

Figure 3. *The influence of material temperature on atomic oscillation (a – the lattice parameter)*

d) Atoms with a higher mass need more energy to start oscillating;

e) Atoms located closer to each other (a small lattice parameter) are more resistant to oscillation;

f) The maximum oscillation amplitude is equal to the lattice parameter;

g) If we consider that a layer of atoms starts oscillating (Fig. 4), which is the actual situation in practice, then the maximum amplitude at which atoms are released from the lattice is also influenced by the resistance of these layers to oscillation.

To assess the machinability of pure substances according to the proposed principle of laser beam interaction with material, the following formulae can be used (in the F force equation we have neglected the gravity constant; the masses of the atoms are the same: $m_1 = m_2 = m$):

$$F = \frac{m^2}{a^2} \qquad \frac{F}{T_t} \qquad \frac{F}{T_v} \qquad (1)$$

where:
F is the force acting on the atom;
m is the atomic mass;
a is the lattice parameter.

The calculated values are listed in Tab. 1.

Conclusion: The smaller the force *F* and the ratios

$$\frac{F}{T_t} \; a \; \frac{F}{T_v}$$

the more easily machinable the material. This can be used as a criterion for assessing machinability and classifying materials within a group into subgroups.

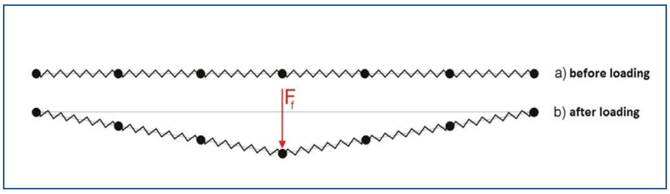

Figure 4. *The size of the impacted area*

As one atom starts oscillating, the position of the neighbouring atoms changes as well; the position basically corresponds to the heat conductivity of the material (Fig. 4). Heat conduction thus also leads to changes in the position of the surrounding atoms in the direction perpendicular to the movement of the beam. Heat is again conducted by the movement of atoms within the lattice. As the oscillation of atoms is rectified rapidly due to the high intensity of the laser light, we can presume that after approximately 1 nanosecond atoms start to oscillate in a very small volume in the direction perpendicular to the laser beam [Yilbas 2001 a 2002].

In practice, more atoms are influenced by the impacting laser beam (laser beam track), i.e. photons do not only act on one atom. The size of the impacted area is defined by ‹attenuation of oscillation› which depends on atomic mass and on the force of attraction between atoms that are not impacted by photons.

2.3 Proposed Theory of Laser Beam Interaction with Material

Preconditions:

- An atom oscillates within the lattice; the impact of a laser beam makes it oscillate only in the direction of the beam (the beam has such intensity as can ‚modify' the oscillation). Before the impact of a laser beam atoms oscillate in an unorganised manner in the direction of the three coordinate axes;
- At a particular temperature an atom oscillates with the corresponding amplitude: the higher the temperature, the higher the amplitude (Fig. 5, $T_1 < T_2$);
- By irradiating material with laser light an oscillating atom receives an additional force from the impact of photons; as different

Crystal lattice type	Substance	Force F acting between atoms	F/T_t ratio	F/T_v ratio	Machinability
hcp	C	11.324	0.003	0.002	1
	Zn	604.31	1.442	0.66	2
ccp	Si	26.75	0.02	0.01	1
	Al	44.38	0.067	0.02	2
	Ni	277.998	0.19	0,1	3
	Cu	309.897	0.28	0.12	4
bcc	Ti	263.43	0.14	0.074	1
	Fe	378.65	0.209	0.1253	3
	Cr	325.95	0.173	0.12199	2

Table 1. *Material machinability according to the oscillation theory*

workpiece materials have different frequencies of atomic oscillation within the lattice in the starting position, the optimum laser beam oscillation frequency varies as well;
- After transmitting its energy, expressed by its pressure on the atom, a photon loses its mass and becomes a wave, thus not increasing the mass of the oscillating atom;
- The force created by the impacting photons acts as the oscillation excitation force (Fig. 6, where t is the time and A is the amplitude).

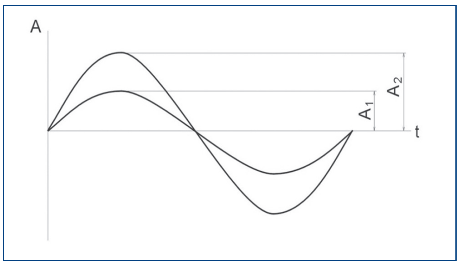

Figure 5. *The influence of temperature on the course of the excitation force*

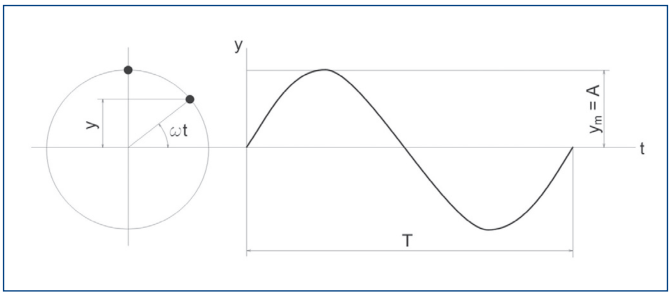

Figure 6. *The course of the excitation force*

Since the interaction of a laser beam with workpiece material (i.e. material removal with a laser beam) is seen as forced oscillation, the process can be described using the equation [Julis 1987]:

$$m_a\ddot{x} + b\dot{x} + k_a x = F_f\ sin\omega t \quad (2)$$

or the rearranged equation

$$\ddot{x} + 2N_k\dot{x} + \Omega^2 x = a_p sin\omega t \quad (3)$$

where:

$$a_p = \frac{F_f}{m_a} \quad (4)$$

$$2N_k = \frac{b}{m_a} \quad (5)$$

$$\Omega^2 = \frac{k}{m_a} \quad (6)$$

$$\omega = 2\pi f_f \quad (7)$$

where:

ω is the angular velocity of the excitation force;
f_f is the laser pulse frequency;
m_a is the atomic mass;
k_a is the constant (stiffness) of 'springs', determined by the forces acting between atoms (for calculations it needs to be negative, because it decreases as the distance between atoms grows), kx = the variable directional force;
b is the attenuation coefficient; bx is the damping force determined by the oscillation of neighbouring atoms which are not impacted by photons (damping caused by the 'transmission of heat to the material and the environment'). For the machining of cavities, depending on the size of the cavity, the laser beam returns to the same place after some time, where increased attenuation (lower amplitude) of atom oscillation occurs, which corresponds to the influence of cooling (it depends on the thermal diffusivity of the workpiece).

For forced oscillating movement the equation for the deflection is as follows:

$$x_p = A\sin(\omega t - \varphi) \quad (8)$$

$$A = \frac{a_p}{\sqrt{(\Omega^2 - \omega^2)^2 + 4N_k^2\omega^2}} \quad (9)$$

$$tg\varphi = \frac{2N_k\omega}{\Omega^2 - \omega^2} \quad (10)$$

where:

A is the amplitude;
φ is the phase angle;
Maximum deflection – resonance

$$x_{\max} = \frac{a_p}{2N_k\sqrt{\Omega^2 - N_k^2}} \geq a \quad (11)$$

where a is the lattice parameter

The force of one pulse

$$F_f = \frac{p}{S_A} = \frac{\text{pressure from photons}}{\text{surface of atom perpendicular to the beam direction}} = \frac{N.m_f.V.\frac{v^2}{3}}{\pi.r_A^2} \quad (12)$$

$$m_f = \frac{h.\nu_f}{c^2} \quad (13)$$

where

N is the Avogadro constant
m_f is the photon mass;
h is the Planck constant
v_f is the laser radiation frequency;
c is the speed of light;
v is the amplitude of a laser beam radiation wave;
V is the volume of the specimen; 4 times the volume of a crystal lattice element;
r_a is the atom radius.

A graphic representation of the influence of damping is shown in Figure 7.

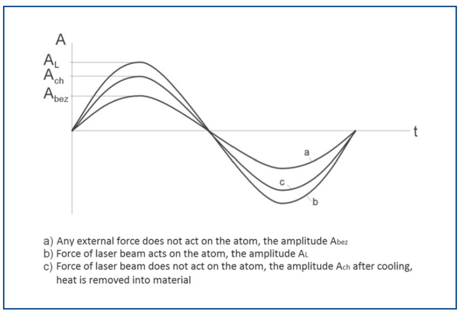

Figure 7. *The influence of damping when creating cavities*

2.4 Description of material removal with a laser beam

A photon flow (laser beam) acts on the crystal lattice of the material. By impacting an atom, photons increase the oscillation amplitude, thus increasing the temperature of the material. In a movable workpiece atoms are impacted by more photons acting in the direction of the laser beam track (Fig. 8).

At an optimum working speed, i.e. the speed of the laser beam moving on the surface of the material, an atom separates from the lattice at the moment when the end of the beam track leaves the original position of the atom. The smaller the beam track, the better the focus and the higher the density of impacting photons.

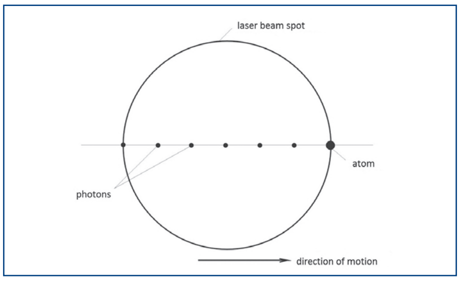

Figure 8. *The course of photon action on an atom within the beam track*

The influence of beam movement speed (working speed) – the following cases can occur:

a) The beam moves at a high speed – the photons are not able to make an atom oscillate to such a degree as to make it separate form the lattice. This is material melting, and the molten material needs to be blown away with auxiliary gas;
b) The beam moves at an optimum speed – the atom separates; this is material evaporation;
c) The beam moves at a too low speed – forces acting between atoms gradually diminish, and melt is created where atoms move in an uncontrolled manner; the capacity of a laser to quickly supply heat energy is not used here, and the process resembles slow heating.

3. A Theory of Laser Beam Interaction with Workpiece Material Based on Change in the Internal Energy of the Crystal Lattice

A number of substance properties have been considered in assessing the machinability of materials, in particular: melting temperature, evaporation temperature, thermal conductivity, density, specific heat capacity, heat diffusivity, specific melting heat, heat of evaporation, absorption coefficient, reflection coefficient, emissivity, atomic mass, first ionisation energy, electronegativity, lattice parameter, atomic concentration, distance between nearest neighbour atoms, cohesion energy, energy required for separating one electron, energy required for separating two electrons, bulk modulus, compressibility, electrical conductivity, specific electrical resistance of metals, natural relative representation, nuclear magnetic moment, proton number, crystal lattice type, electron configuration, nuclear spin, atomic radii for tetraedric covalent bonds, ion radii in a valence state marked with superscript, electron heat constant of metals as observed, electron heat constant of metals for free electrons as calculated, isothermal bulk modulus, and isothermal compressibility. We also tried to apply the theory of impact.

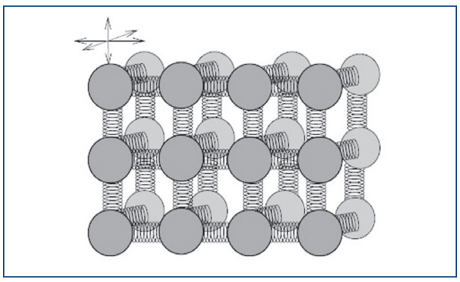

Figure 9. *Springs and atoms*

The proposed oscillation-based theory of laser beam interaction with material surface provides the possibility to base assessment upon changes in the internal energy of the crystal lattice after the energy of impacting photons is transmitted. One model has been created by Einstein and elaborated by Debye [Opatrny 2000]. We will use Debye's model for assessment purposes (Fig. 9).

After rearrangement, the internal energy of a crystal for high temperatures is as follows:

$$E \approx 3N\boldsymbol{h}\omega_m \frac{T}{\theta} = 3Nk_B T \qquad (14)$$

Heat capacity of the lattice:

$$C_V = 3Nk_B \qquad (15)$$

where:

N is the number of oscillating particles;

$$N = \frac{\text{laser beam diameter}}{\text{lattice parameter}} \qquad (16)$$

h is the Planck constant;
ω_m is the maximum value of pulse frequency;
T is the evaporation temperature of the material;
θ is the Debye temperature;
k_B T is the mean value of oscillator energy.

For our laser the diameter of the beam track is 0.1 mm.

Since this criterion depends on the properties of the crystal lattice and the number of oscillating atoms, the approach to machinability can be based on energy transmission and absorption. This is, in fact, the kinetic energy of oscillating atoms within the crystal lattice.

For our calculations:
h is the same for each neighbouring atom, as pure substances are considered;
ω_m is the laser pulse frequency; one frequency was used for testing

To determine relative machinability, i.e. to determine which material is easier to machine, we can use a simplified formula, not considering the quantities h and wm. Then the following applies:

$$E = 3N\frac{T}{\theta} \qquad (17)$$

A laser ensures very intense heat supply whereby atoms start oscillating predominantly in one direction, parallel with the laser beam; then we can leave number 3 out of the equation. For substitution we will use the substance values listed in Tab. 1.

The calculated values of crystal internal energy after laser beam irradiation are listed in Tab. 2.

Substance	N	E
Fe	3.48857*10^5	69.7862*10^5
W	3.15935*10^5	138.0952*10^5
Cr	3.43642*10^5	48.17534*10^5
C	4.05844*10^5	23.4771*10^5
Zn	3.75248*10^5	40.62318*10^5
Ti	3.38891*10^5	86.17514*10^5
Cu	2.76632*10^5	77.4247*10^5
Ni	2.83768*10^5	60.27232*10^5
Pb	2.01987*10^5	116.6908*10^5
Al	2.46944*10^5	48.32717*10^573,94773*10^5
Sn	1.71473*10^5	73.94773*10^5
Si	1.84131*10^5	27.17431*10^5

Table 2. *Crystal internal energy*

Assessment is made for each crystal lattice type, from the most easily machinable substances to the least easily machinable ones.

- lattice **hcp**, order of substances: C Zn Ti
- lattice **ccp**, order of substances: Si Al Ni Cu
- lattice **bcp**, order of substances: Cr Fe W

Concluding observation: for each crystal lattice type the following applies: the smaller the value of the crystal internal energy, the better the machinability of the substance.

Conclusion

Based on experimental research on laser machinability of materials, a theory of laser beam interaction with the surface of a material sample has been proposed. The theory is based on the dependence of atomic oscillation on the temperature of the sample. The process has been understood as forced oscillation with a growing oscillation amplitude. An equation describing the maximum deflection (amplitude) at which an atom is separated from the lattice has been presented. Since the proposed theory sees the interaction as oscillation, we have also verified the possibility to use the internal energy of a crystal lattice for describing and assessing the laser machinability of materials.

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