PROPOSED EVALUATION OF MATERIAL MACHINABILITY USING A LASER BEAM

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The article presents the results of research on laser machinability of materials. The research has been carried out on pure substances, namely C, Zn, Ti, Si, Al, Ni, Cu, Fe, Cr, as well as different types of steel, cast iron, bronze, brass and titanium alloys. A diode-pumped solid-state Ns:YAG laser with a medium output power of 50 W has been used as the radiation source. Based on experimental results, a method for defining and evaluating laser machinability of materials has been proposed, including the classification of materials in corresponding machinability classes. The definition method is based on the crystal lattice type of the material. The impact of working speed and laser pulse frequency on machinability has been assessed.

Keywords
Laser, machinability of materials, pure substances, alloys, impact of working speed, impact of pulse frequency

1. Introduction

Laser machinability is an important material property which makes it possible to determine optimum working conditions (power, working speed, pulse frequency and duration), thus ensuring efficient machining. Machinability is currently assessed using differential equations based predominantly on heat conduction, or equations derived from experiments. This article proposes an evaluation method based on the physical properties of materials. The proposed machinability evaluation method is as follows:

a) classifying materials into main groups based on the type of their crystal lattice;
b) each group has 10 subgroups, where subgroup 1 contains materials that are the most difficult to machine, and group 10 those that are the easiest;
c) within each subgroup materials are grouped by their heat conductivity, melting temperature (cutting operations) and evaporation temperature (micro-milling and engraving operations).

2. Literature review

In the literature, the machinability of materials with a laser beam is evaluated using differential equations based on information about heat transfer, or equations derived from experiment results.

However, the differential equations mentioned in the literature [Yilbas 2001] mostly rely on physical parameters whose values are not known for all materials. An example of the form of the differential equations mentioned:

$$\frac{\partial^2}{\partial x^2}T(x,t)+\frac{I_1\delta}{k}\cdot\left(e^{-\beta\cdot t}-e^{-\gamma\cdot t}\right)\cdot e^{-\delta\cdot x}=\frac{1}{\alpha}\cdot\frac{\partial}{\partial t}T(x,t) \qquad (1)$$

where:
T(x, t) is the temperature [K]
I_1 – the intensity of radiation [Wm^{-2}]
k – the thermal conductivity [$Wm^{-1}K^{-1}$]
δ – the absorption coefficient [m^{-1}]
x – the distance from the surface [m]
t – the time [s]
α – the thermal diffusivity [m^2s^{-1}]
γ – the relaxation time [s^{-1}]
β – the relaxation time [s^{-1}]

To solve the equation, it is important e.g. to enter the boundary conditions and express the shape of radiations pulses (for this, the reflection coefficient needs to be known); some researchers neglect e.g. the relaxation times β and γ.

A different evaluation method uses equations derived from experiment result which, however, are only valid for the working conditions under which the experiments have been carried out. The following information and equations are mentioned in the literature [Chryssolouris 1991]:

(a) going deeper into the material, the radiation intensity of the laser beam decreases according to this relation:

$$I = I_0 \cdot e^{-\alpha x}\ [W.m^{-2}] \qquad (2)$$

where
I_0 is the laser beam intensity [$W.m^{-2}$]
α – the optical absorptivity coefficient of the material
x – the depth of the material [m]

(b) the penetration depth of radiation in the material, i.e. the depth where almost all incident energy is absorbed, is determined by the relation

$$\delta = 2 / \alpha\ [m] \qquad (3)$$

where
α is the optical absorptivity coefficient of the workpiece material.

For metals, this optical penetration depth is approx. 10nm, which means that the energy of the laser beam heats up a metal layer by 10 nm in 1 ps. The heat produced in this way tends to diffuse towards the inside of the material;

(c) according to another source, the diffusion depth is determined by the relation:

$$d = (4\beta\ .\ t)^{1/2}\ [m] \qquad (4)$$

where
β is the thermal diffusivity [$m^2.s^{-1}$]
t – the diffusion time [s]

(d) according to the literature [Sadowski 1977], the penetration depth is determined by the relation

$$R = 503\ (\mu \times \gamma \times f)^{-0,5}\ [mm] \qquad (5)$$

where
μ is the relative magnetic permeability of the machined material
γ – the specific electrical conductivity of the machined materiál [$m.\Omega^{-1}.mm^{-2}$]
f – the radiation frequency [Hz]

(e) the literature also says that for steel, a diffusion depth of 1 nm is achieved in 10 fs, as during one impulse of 1 ps the heat diffuses into the depth of 10 nm;

(f) the optical penetration depth depends on the material and the wavelength of the laser radiation;

(g) the depth of diffusion depends mostly on the properties of the material;

(h) for steel, the expected material removal rate (based on physical considerations) is 10 nm/impulse for energy density H = 1 J/cm². Experiments have, however, shown a higher removal rate: for H =

4 J/cm^2 the removal rate was 50 nm/impulse, and for H = 14 J/cm^2 it was 350 nm/impulse (the authors consider this as the limit of material saturation). They assume the differences are due to plasma (cited from Semak [Wikipedia]);

(i) Omura [Wikipedia] studied aluminium, copper and silicon at the laser radiation wavelength of 266 nm. The optical penetration depth ranged from 5 to 50.10^9 W/cm^2. The experiment showed that the material evaporates in the form of particles ranging from 0.3 to 10 nm in size; most of them are smaller than 1 nm. The average speed of particles flying off the material is several km/s and more. There are also particles with negative speed which return to the material surface and create burrs.

3. Research at the Faculty of Mechanical Engineering of CTU in Prague

The Research Center of Manufacturing Technology of the Faculty of Mechanical Engineering, CTU in Prague, has carried out experiments which involved laser machining of different types of steel, cast iron, brass, bronze and titanium alloys. These experiments have clearly shown that the machinability of a material depends on the content of individual chemical elements. This is why we have oriented our further experiments towards the machining of pure substances.

3.1 The machinability of alloys

An Nd:YAG laser with an output power of 50W and wavelength λ = 1,06 µm was used for the experiments. The baseline machining conditions were: laser beam feed rate of 20, 40, 60,80 a 100 mm/s, power of 50 W, and pulse frequency of 4,500 Hz. The dimensions of the machined surface were 10 x 10 mm, the number of material removals (i.e. the number of removed layers) was 55. The machinability was evaluated based on the depth of the resulting cavity: the deeper the cavity, the better the machinability. The cavity depth was measured by a digital indicator (accuracy 0,001 mm) at five random locations of cavity bottom and the depth of selected cavities was measured by an optical measuring device.

For experiments with iron-based materials, materials with different contents of carbon were selected, ranging from 0.068 to 3.65%. An overview of the materials examined is provided in Tab. 1.

There was a changing content of Al and Zn in CuAl and CuZn alloys. The content of basic elements for the CuAl alloys is shown in Table 2, and for CuZn alloys in Tab. 3.

A comparison between the machinability of iron and that of carbon is shown in Fig. 1; the machinability dependence for a FeC alloy is depicted in Fig. 2. Both charts show that machinability improves with increasing content of carbon (a substance with better machinability).

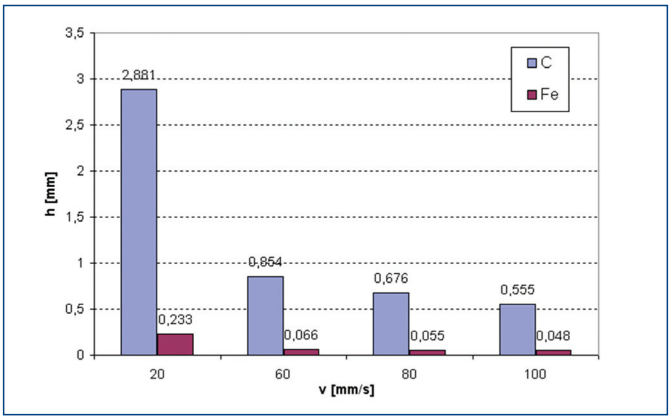

Figure 1. *Dependence of material removal on laser beam speed (C, Fe)*

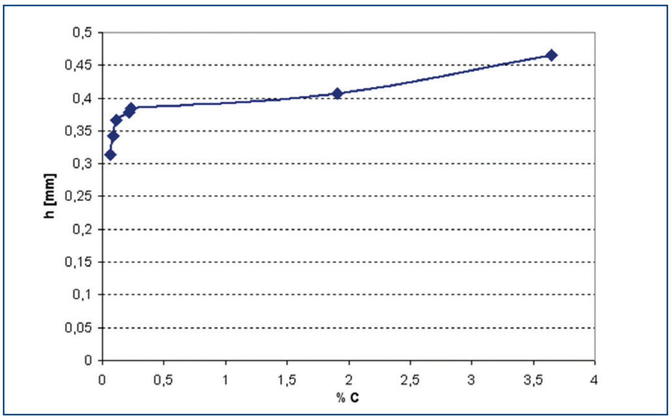

Figure 2. *Dependence of material removal on carbon content in the alloy*

A comparison between the machinability of copper, aluminium and zinc is shown in Fig. 3; Fig. 4 illustrates the machinability dependence for a CuAl alloy, and Fig. 5 for a CuZn alloy. Again, it is evident from both charts that with increasing content of a well-machinable chemical element the machinability of an alloy improves.

The same experiments have been performed with TiAl alloys. The chart in Fig. 6 illustrates the dependence of cavity depth on working speed for pure titanium and aluminium. The chart in Fig. 7 shows the dependence of cavity depth on the content of aluminium in the alloy. Again, the general conclusion is that with increasing content of a well-machinable chemical element the machinability of an

Chem. elements	Materials examined – designation as per Czech National Standards (ČSN)						
	10 505	11 300	11 320	11 343	14 220	19436	42 2420
Fe	98.56	99.36	99.35	99.14	96.92	85.94	93.84
C	0.23	0.087	0.068	0.11	0.22	1.91	3.65

Table 1. *Iron-based alloys*

Chem. elements	Materials examined			
	CuAl3	CuAl5	CuAl9	CuAl13
Cu	96.79	94.88	90.85	86.89
Al	3.134	5.033	9.067	13.026

Table 2. *CuAl alloys*

Chem. elements	Materials examined				
	CuZn10	CuZn20	CuZn30	CuZn40	Cu99.9E
Cu	89.36	79.13	70.16	60.50	99.9
Zn	10.54	20.787	29.681	39.404	0.078

Table 3. *CuZn alloys*

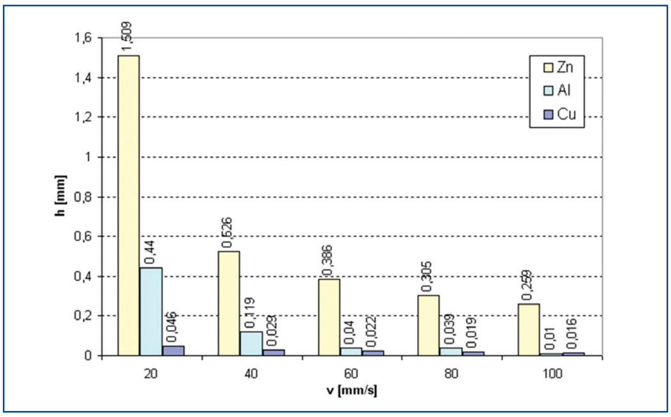

Figure 3. *Dependence of material removal on speed (pure substances – Zn, Al, Cu)*

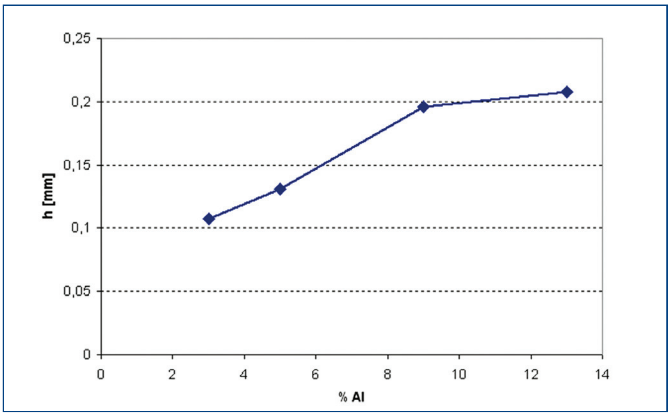

Figure 4. *Dependence of material removal on Al content*

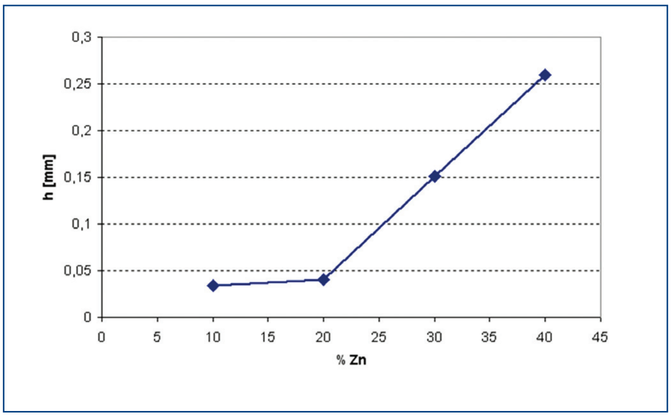

Figure 5. *Dependence of material removal on Zn content*

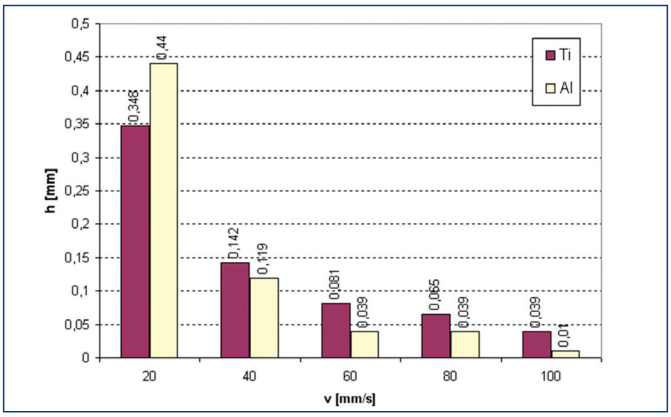

Figure 6. *Dependence of material removal on speed (Al, Ti)*

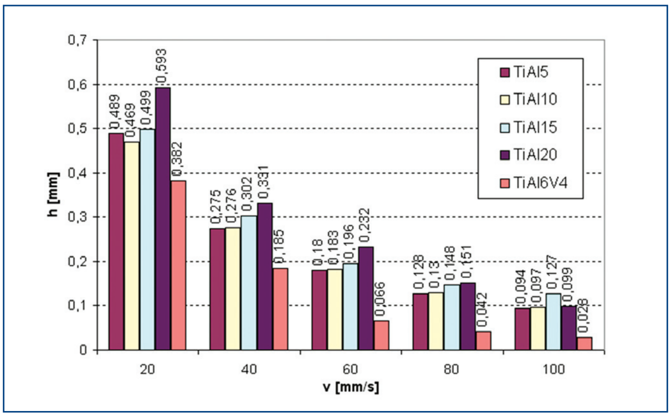

Figure 7. *Dependence of material removal on speed (TiAl alloys)*

alloy improves. For comparison purposes, the chart shows the machinability of the TiAl6V4 alloy.

The experimental results have been transformed into equations which make it possible to calculate the cavity depth for a given material, working conditions and number of material removals [Rasa 2006, 2007, 2008, 2009, 2010 a 2011]. The resulting equations also make it possible to determine the machinability of a material by comparing the number of removals needed for a particular cavity depth for two or more materials. The limitation of this method consists in the fact that it can only be used for the materials examined. For other materials and working conditions further experiments need to be carried out. Examples of derived equations:

(a) steel 14 220
$h = -0.0072n + 0.0397$ determination coefficient $R^2 = 0.9991$ (6)

(b) steel 19 436
$h = -0.0075n + 0.0512$ determination coefficient $R^2 = 0.9890$ (7)

(c) cast iron 42 2420
$h = -0.0083n + 0.0542$ determination coefficient $R^2 = 0.9949$ (8)

In the equations:
h – is the depth of the resulting cavity [mm]
n – is the number of material removals (i.e. the number of times the laser beam passes over the machined surface)

3.2 The machinability of pure substances

Further research has focused on the study of pure substances with the aim of determining the property/properties that characterise their machinability. Experimental machining of pure substances was performed under the same working conditions as the experiments with alloys. The substances were arranged on a scale according to cavity depth, from the deepest to the shallowest. Then selected substance properties were attributed to the substances on the scale. The following properties were studied: melting temperature; evaporation temperature; thermal conductivity; density; specific heat capacity; thermal diffusivity; specific melting heat; heat of evaporation; type of crystal lattice; lattice parameter; atomic concentration; distance between nearest neighbour atoms; element type; element group; period; atomic mass; first ionisation energy; electronegativity; electron configuration; electrical conductivity; specific electrical resistance; nuclear spin; natural relative representation; nuclear magnetic moment; standard ionic radii in noble gas configuration; atomic radii for tetraedric covalent bonds; ion radii in a valence state; Debye temperature; electron heat constant of metals as observed; electron heat constant of metals for free electrons as calculated; cohesive energy; energy required for separating one electron; energy required to separate two electrons; isothermal bulk modulus; isothermal compressibility; absorption coefficient; reflection coefficient; emissivity; experimental electron heat constant of metals; specific electrical resistance of metals; electronegativity; electron configuration, number of free (bonding) electrons; proton number; and speed of sound propagation in materials.

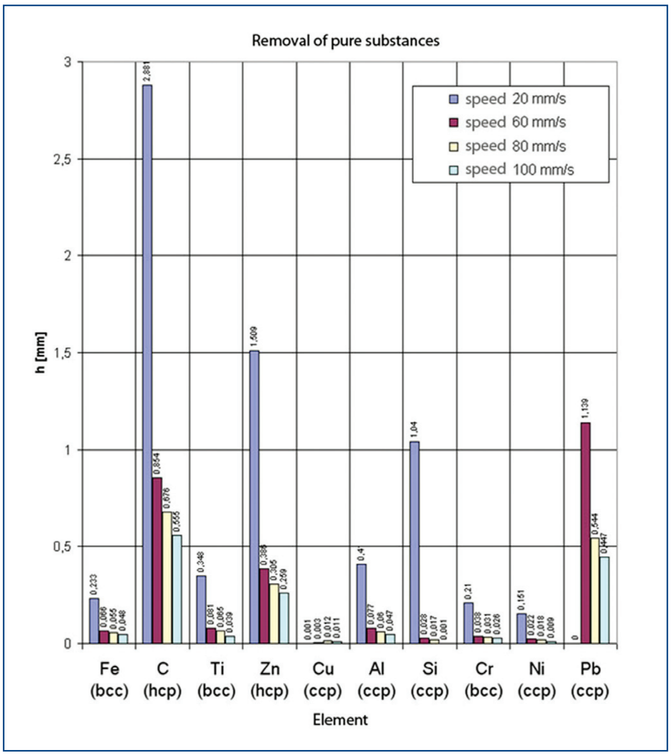

Figure 8. *Machinability of pure substances depending on the type of crystal lattice and laser beam working speed*

For all the substances examined, the experimental results were evaluated from the point of view of all the above-mentioned properties. The evaluation showed that no property, or combination of properties, corresponded to the experimentally determined machinability based on cavity depth. A criterion for determining the machinability of materials with a laser beam was only found after the substances were divided into groups according to their crystal lattice (Fig. 8).

There are two conclusions to be drawn from the experimental results:

a) with a growing percentage of a well-machinable substance in an alloy its machinability improves up to a certain percentage of the substance (see the charts in Fig. 2, 4 and 5);
b) the machinability of pure substances depends on their crystal structure. This is the only substance property that corresponds with the removal rate. Other examined properties cannot be used on their own to evaluate the machinability of materials.

3.3 Proposed evaluation method for the machinability of materials with a laser beam

Based on the experiments performed, we propose the following method for evaluating the machinability of materials with a laser beam:

a) classify the materials into groups according to their crystal lattice; for the materials we have examined these groups are: ccp, bcc, and hcp
b) each group would consist of 10 subgroups, where subgroup 1 includes the materials that are the most difficult to machine, and subgroup 10 those whose machining is the easiest.

To divide metallic materials into subgroups within a group, the following material properties can be used:

a) melting temperature – for material cutting;
b) evaporation temperature – for micro-milling and engraving.

Tab. 4 clearly shows that these properties produce the same substance order as the cavity depth parameter.

Lattice type	**hcp**	**ccp**	**bcc**
Order acc. to cavity depth	C Zn Ti	Si Al Ni Cu	Fe Cr
Melting temperature	C Zn Ti	Si Al Ni Cu	Fe Cr
Evaporation temperature	C Zn Ti	Si Al Ni Cu	Fe Cr

Table 4. *Properties with same substance order as the cavity depth parametr*

The division of materials into machinability classes can also be done experimentally. Experiment conditions:

- working speed of laser beam feed: 20 mm.s^{-1};
- pulse frequency: 4 500 Hz;
- number of removals: 55;
- dimensions of machined cavity: 10 x 10 mm;
- laser output power: 50 W.

It needs to be added that the absolute material removal rate for laser beam machining depends on the working speed of the laser feed and on the pulse frequency. This fact is illustrated in the following tables.

Acc. to cavity depth		**Substance order from best machinability to worst**		
		lattice hcp C Zn Ti	**lattice ccp Si Al Ni Cu**	**lattice bcc Fe Cr**
Speed (mm/sec)	20	C Zn Ti	Si Al Ni Cu	Fe Cr
	60	C Zn Ti	Al Si Ni Cu	Fe Cr
	80	C Zn Ti	Al Ni Si Cu	Fe Cr
	100	C Zn Ti	Al Cu Ni Si	Fe Cr

Table 5. *The influence of working speed*

This is well illustrated in the case of silicon, where machinability worsens with increasing working speed. This may be explained by the fact that with increasing working speed the number of photons impacting an atom in the crystal structure decreases.

In general, the material removal rate for all materials drops with increasing working speed. The frequency varied from 1000 to 8000 Hz; no removal occurs above the latter value. LASER working parameters: power: 50 W; number of removals: 55; working speed: 40 mm/sec.

The table shows that for each pulse frequency the order of materials according to their machinability is the same; what differs is the absolute value of cavity depth.

Frequency (Hz)	**1000**	**1500**	**2000**	**2500**	**3000**	**3500**	**4000**	**4500**	**5000**	**6000**	**8000**
Al – removal depth **h**	0.029	**0.104**	0.06	0.069	0.084	0.076	0.029	**0.119**	0.013	0.046	0.049
Cu – removal depth **h**	0.018	**0.040**	0.032	**0.035**	0.034	0.020	0.016	0.029	0.001	0.001	0.001
Zn – removal depth **h**	0.102	---	0.279	0.331	0.401	0.476	0.572	0.626	0.666	0.796	**1.072**
Ti – removal depth **h**	---	---	---	---	0.051	---	0.105	0.142	0.131	0.142	**0.137**

Table 6. *The influence of beam pulse frequency on the order of materials according to machinability*

Since crystal structure is the main criterion of material machinability, calculations can also be used to classify materials into basic groups. The calculation is based on the following consideration: a stream of photons (i.e. a laser beam) impacts the material surface which tries to deform its crystal lattice until an atom is separated from the lattice.

The proposed method for evaluating the machinability of metallic materials according to the resilience of their crystal lattice is based on the following consideration:

- the main resistance against the deformation of the crystal lattice occurs in the direction perpendicular to the direction in which the photons act, i.e. perpendicular to the workpiece surface;
- the magnitude of forces interacting among atoms in the lattice decreases with growing distance.

Analysis can be performed on two levels:

a) only lattice resistance determined by the force acting between two atoms positioned one above the other is considered (Fig. 9);
a) forces from all atoms surrounding the one under examination are considered (Fig. 10);

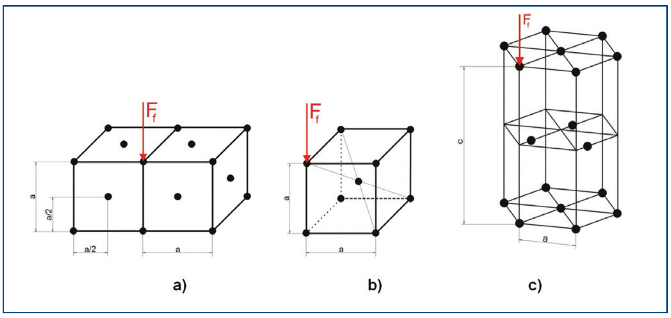

Figure 9. *Crystal lattice types*

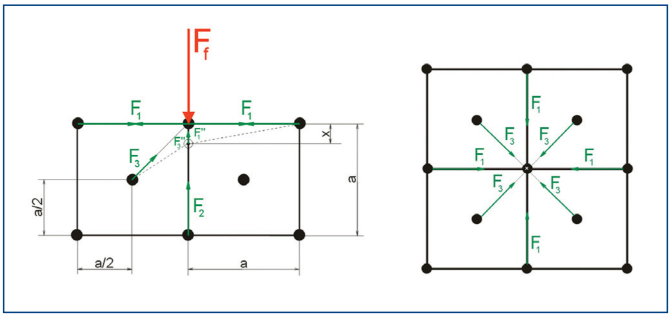

Figure 10. *ccp lattice – balanced forces (left: side view, right: top view)*

The force acting between atoms is determined by the following relation:

$$F = \kappa \frac{m_1 m_2}{a^2} \tag{9}$$

This seems to imply that:

a) with increasing atom mass material machinability worsens;
a) with decreasing lattice constant value (i.e. the distance between atoms) material machinability worsens.

In reality, however, this is not so simple, as valence electrons, which participate in the creation of plasma, also play a role. For pure substances the following simplified equation can be used:

$$F = \frac{m^2}{a^2} \tag{10}$$

because κ is a constant value for all materials, and $m_1 = m_2$.

From calculations performed according to point (a) for the materials under examination we have obtained results listed in tab. 7, 8 and 9.

Substance	Calculated force	Order acc. to depth
Si	26.7525	1
Al	44.3837	2
Ni	278.03	3
Cu	309.8575	4
Pb	1752.1412	Cavity not formed

Table 7. *Substances with crystal lattice (ccp)*

Substance	Calculated force	Order acc. to depth
Ti	104.6686	1
Cr	325.9542	2
Fe	378.6482	3

Table 8. *Substances with crystal lattice (bcc)*

Substance	Calculated force	Order acc. to depth
C	11.3384	1
Zn	174.5068	2

Table 9. *Substances with crystal lattice (hcp)*

The tables show that the criterion is usable for a given lattice.

Since the laser beam moves in relation to the machined surface, the whole process is a dynamic one. This consideration has brought us to study the interaction between the laser beam and the surface of the machined material from the point of view of crystal lattice behaviour.

Conclusion

Machinability of materials was evaluated using the depth of a laser-produced cavity. The aim was to find a property or properties which could be used to assess machinability. 47 element properties were analysed in total; none of them taken on its own proved suitable for the evaluation of machinability. When we divided the elements into groups according to the type of their crystal lattice, the order of the elements sorted by the depth of the produced cavity corresponded to their order according to thermal conductivity and melting and evaporation temperatures. Based on this result, we have postulated a definition of machinability of materials and a metodology for its determination. The result of the research led us to study the mechanism of the effect of the laser beam on the surface of the machined material.

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References

Book:

[Beyer 1998] Beyer, E., Wissenbach, K.: *Laser surface treatment, laser technics and reserch,* Springer-Verlag Berlin Heidelberg, 1998 (in German)

[Furbacher 1997 – 2006] Furbacher, I., Macek, K. steidl, J.: *Lexicon technical Materials*. Dashöfer Holding, Ltd. A Verlag Dashöfer, 1997–2006 (in Czech)

[Grigirjan 1987] Grigorjan, A. G., Safonov, A. N.: *Methods of laser beam treatment,* 3rd part, Moscow, 1987 (in Russian)

[Halliday 2000] Halliday, D., Resnick, R., Walker, J.:Physics, VUT Brno, *VUTIUM and PROMETHEUS,* Prague, 2000 (in Czech)

[Chryssolouris 1991] Chryssolouris, G.: Laser Machining: Theory and Practice, Springer-Verlag New York Inc, ISBN 3-540-97498-9, 1991

[Michalek 2009] Michalek, L.: *Fundamentals of Matter,* e-mail: michalek@worldonline.cz (in Czech)

[Palik 1985 – 1998] Palik, E.D,: *Handbook of Optical Constants of Solids I, II, III.* ISBN 0–12-544423-0. Academic Press. Florida, USA. 1985–1998

[Sadowski 1977] Sadowski, A., Krehlik, R.: *Laser in Machining and Metrology*, SNTL, Prague, 1977 (in Czech)

[Yilbas 2001–1] Yilbas, B. S., Kalyon, M.: *Analytical Solution for Pulsed Laser Heating Process: Convective Boundary Condition Case.* 2001

Paper in a journal:

[Yilbas 2001] Yilbas, B. S.: *A Closed Form Solution for Temperature Rise Inside Solid Substrate due to Time Exponentially Varying Pulse.* International Journal of Heat and Mass Transfer. 2001

[Yilbas 2002] Yilbas, B. S., Shuja, S. Z., Arif, A., gondal, M. A.: *Laser-Shock Processing of Steel.* Journal of Materials Prtocessing Technology. 2002

Technical reports or thesis:

[Hovorkova 2003] Hovorkova, Z.: *Laser- beam interactions with Material of Workpiece,* Research report RCMT 5-06-03, Prague, 2003 (in Czech)

[Rasa 2002] Rasa, J., Kraus, L., Jindrova, R.: *Laser- beam interactions with Material of Workpiece,* Research report RCMT 05-03-02, Prague, 2002 (in Czech)

[Rasa 2004] Rasa, J., Hovorkova, Z., Jindrova, R.: *Research of Laser Micro- Milling Conditions,* Research report RCMT 05-02-04, Prague, 2004 (in Czech)

[Rasa 2006] Rasa, J., Kerecaninova, Z.: *Metal Non – Iron Material Behaviour during Laser Machining*, Research report RCMT V-06-035, Prague, 2006 (in Czech)

[Rasa 2007] Rasa, J., Kerecaninova, Z.: *Metal Non – Iron Material Behaviour during Laser Machining,* Research report RCMT V-07-037, Prague, 2007 (in Czech)

[Rasa 2008] Rasa, J., Kerecaninova, Z.: *Machinability of Titanium and Titanium Alloys by Laser,* Research report RCMT V-08–20, Prague, 2008 (in Czech)

[Rasa 2009] Rasa, J.: *Influence of Elements on Laser Metal Workability,* Research report RCMT V-09-046, Prague, 2009 (in Czech)

[Rasa 2010] Rasa, J.: *Machinability of Metal Materials by Laser.* Research report RCMT V–10-036. Prague 2010 (in Czech)

[Rasa 2011] Rasa, J.: *Laser Beam Interaction with Material.* Research report RCMT V–11-043. Prague 2011 (in Czech)

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