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Empirical relations and figure of merit functions for thermal material processings with high-power lasers

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Simple empirical relations are presented for laser cutting and welding. The systematic search and use of such relations could lead to a better understanding and simplifying of the parametric studies for laser thermal material processing. A proper figure of merit (FOM) function can be used to characterize the thermal properties of materials. Several options of FOM functions are considered.

1. Introduction

The focused laser beam is one of the highest power density sources available to industry today. It is one of the most flexible and easily automated industrial energy sources. Today, it is used in material processing, such as cutting, welding, and heat treatment [1].

Material processings with high-power laser radiation can be classified into nonreactive thermal processing and reactive chemical processing [2]. Thermal processing is essentially the heat treatment performed in a vacuum or in any ambience. It involves the interaction of laser radiation with matter with subsequent absorption of radiation and rapid thermalization resulting possibly in melting, vaporization, or removal of matter from the interaction zone.

The optimum parameters for material processings are determined experimentally. Nevertheless, it is a very time-consuming method as each material and each thickness requires a new experimental run. With the help of empirical relations the processing parameters can be calculated approximately, so that the efforts to optimize these parameters in the laboratory are reduced to a minimum. Simple empirical relations for the most important material processings are shown in this paper. They constitute also a comfortable mode of experimental data presentation and registration for control purposes.

The parametric studies of different thermal material processings can be correlated to meet an increased flexibility of laser devices for various operations. In these studies, a proper figure of merit function can be used to characterize the thermal properties of materials, especially that some of them are not well known for many materials. Several options of FOM functions are considered in this paper.

2. Empirical relations for laser cutting and welding

A simple empirical relation for laser cutting has been obtained for a variety of polymers [3]. It has been shown that a good prediction of the cutting speeds possible at different thicknesses and powers can be obtained from the empirical relation

$$V = \alpha P t^{-1.35} \tag{1}$$

where V is the maximum cutting speed in m/min, P is the laser power in Watts, t is the material thickness in mm, and α is an experimentally derived constant for the polymer. The accuracy of this calculation is better than 10% for most polymers. An empirical relation of the same type

$$V = \alpha P t^{-\beta} \tag{2}$$

with the same units for parameters as in Eq. (1) and $\beta = 1$ can be inferred from experimental data for laser cutting of glass and aramid fibre reinforced plastics [4].

A least-saquare fitting subroutine applied to experimental data of CO_2-laser cutting of different materials [5]–[9] led to the results shown in Tab. 1.

Table 1. Values of β from Eq. (2) obtained by least-square fitting of different experimental cutting data

Material	Value of β	Reference	Average value of β
Carbon steel	1.086	[5]	0.989
	1.024	[5]	
	0.936	[5]	
	0.986	[5]	
	0.977	[5]	
	0.983	[5]	
	1.040	[6]	
	0.887	[7]	
Mild steel	1.789	[5]	1.785
	1.782	[6]	
Aluminium and aluminium alloys	2.112	[8]	2.102
	2.008	[9]	
	2.175	[9]	
	2.113	[5]	

Although the material welding with high-power lasers is a more complex process, we tried to infer a simple empirical relation from experimental data presented as graphical charts [5], [10]–[12]. At low speeds the following dependence is used in predicting required powers and speeds of welding [1], [13]

$$6.3/X = \ln(4.5/Y) \tag{3}$$

where X and Y are normalized power and speed, respectively:

$$X = Q/(tKT), \tag{4a}$$

$$Y = Vb/\varkappa \tag{4b}$$

where: Q is the heat input per unit time, K is the thermal conductivity, T is the temperature, t is the material thickness, V is the welding speed, b is the weld width, and $\varkappa$ is the thermal diffusivity. Then, a good prediction of the welding speeds possible at different thicknesses could be obtained from the relation

$$\ln V = At^{-\beta} \tag{5}$$

where V is the welding speed in m/min and t is the thickness in mm. Results are shown in Tab. 2 for steels welded with CO_2 and Nd:YAG lasers. The lower value of β obtained in the case of Nd:YAG laser could be explained by the higher absorption of steel at 1.06 μm than at 10.6 μm [1].

Table 2. Values of β from Eq. (5) obtained by least-square fitting of different experimental welding data

Laser	Material	Value of β	Reference	Average value of β
CO_2 laser	302 St. Steel	0.314	[10]	0.314
	AISI 304 Steel	0.346	[11]	0.371
		0.396	[12]	
	430 St. Steel	0.521	[5]	0.409
		0.552	[5]	
		0.358	[5]	
		0.312	[5]	
		0.303	[5]	
	$FePO_4$ Steel	0.476	[5]	0.408
		0.359	[5]	
		0.382	[5]	
		0.485	[5]	
		0.420	[5]	
		0.326	[5]	
Nd:YAG laser	St. Steel	0.236	[5]	0.258
		0.296	[5]	
		0.241	[5]	

A systematic search and use of simple empirical relations with easy access to computers for different experimental conditions could lead to a better parametric understanding of material processings with high-power lasers.

3. FOM function for laser thermal material processings

A simple and straightforward method to compare the laser thermal processings of different materials is the use of FOM functions. The parameter $S_0 = c_p T_{H0}$ in units of Joules per gram corresponding to a specific cutting energy has been used [13], [14] in order to compare the laser cutting of different materials, where c_p is the specific heat of the solid and T_{H0} is the temperature which characterizes the process.

The power balance of laser thermal processings reveals that the most important is the heating term [15]

$$P_T = b t V \rho c_p (H_{H0} - T_0) \tag{6}$$

where b is the width of processed region (as, for example, in the case of laser cutting b is the width of the cutting kerf), t is the thickness, ρ is the density, and T_0 is the temperature of the environment. The characteristic temperature T_{H0} can be different for various processing operations. It could be, for example, the melting point T_m, or an average between the vaporization and melting points of the workpiece, $T_{H0} = (T_m + T_v)/2$.

Then, the FOM function for a laser thermal material processing characterized by the temperature T_{H0} could be defined

$$\mathrm{FOM}(T_{H0}) = \rho c_p T_{H0} = C_v T_{H0}, \quad (\mathrm{J/cm^3}) \tag{7}$$

where $C_v = \rho c_p$ is the volume heat capacity. This FOM function has the meaning of a specific laser processing energy.

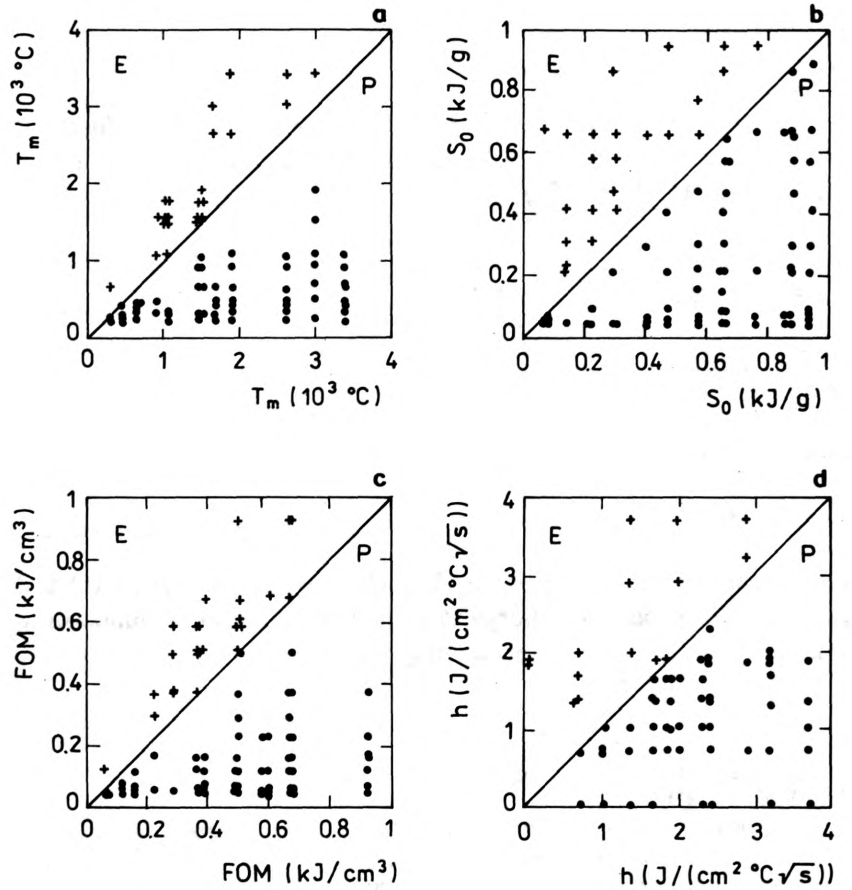
Next, we consider the process of dissimilar metal welding. It was chosen because of its strong dependence on the thermal properties of materials. The laser welding of dissimilar metals is only possible for certain combinations as shown in Tab. 3 [1], [2]. The two extreme cases of excellent (E) and poor (P) weldability are considered.

Table 3. Laser weldibility of dissimilar metal combinations [1]

	W	Ta	Mo	Cr	Co	Ti	Be	Fe	Pt	Ni	Pd	Cu	Au	Ag	Mg	Al	Zn	Cd	Pb	Sn
W																				
Ta	E																			
Mo	E	E																		
Cr	E	P	E																	
Co	F	P	F	G																
Ti	F	E	E	G	F															
Be	P	P	P	P	F	P														
Fe	F	F	G	E	E	F	F													
Pt	G	F	G	G	E	F	P	G												
Ni	F	G	F	G	E	F	F	G	E											
Pd	F	G	G	G	E	F	F	G	E	E										
Cu	P	P	P	P	F	F	F	F	E	E	E									
Au	–	–	P	F	P	F	F	F	E	E	E	E								
Ag	P	P	P	P	P	F	P	P	F	P	E	F	E							
Mg	P	–	P	P	P	P	P	P	P	P	P	F	F	F						
Al	P	P	P	P	F	F	P	F	P	F	P	F	F	F	F					
Zn	P	–	P	P	F	P	P	F	P	F	F	G	F	G	P	F				
Cd	–	–	–	P	P	P	–	P	F	F	F	P	F	G	E	P	P			
Pb	P	–	P	P	P	P	–	P	P	P	P	P	P	P	P	P	P	P		
Sn	P	P	P	P	P	P	P	P	F	P	F	P	F	F	P	P	P	P	F	

(E excellent, G good, F fair, P poor, – no data available)

Different options of parameters characterizing thermal processing are taken into account: the melting temperature T_m, the parameter $S_0 = c_p T_m$, the heat storage coefficient $h = K/\sqrt{\varkappa}$ [16] (where K and $\varkappa$ are the thermal conductivity and diffusivity, respectively), and the $\mathrm{FOM}(T_{H0})$ function defined by Eq. (7) with



Diagrams showing the values of different parameters: **a** — T_m, **b** — $S_0 = c_p T_m$, **c** — $\text{FOM}(T_m) = \rho c_p T_m$, and **d** — $h = K/\sqrt{x}$, for the two metals which form the excellent (E) and poor (P) weldable dissimilar metal combinations. The diagonal lines correspond to null differences between the values of the parameters for the two metals of E and P combinations

$T_{HO} = T_m$ and $T_{HO} = (T_m + T_v)/2$. Values of these parameters [17] for E and P combinations are shown in the Figure. In each diagram of this figure the diagonal line corresponds to the null differences between the parameter values of the two materials which form either an E or P combination.

One can see that when the parameters S_0 and h are chosen to characterize the process, the deviations of the points as against the diagonal lines are not appreciably different for E and P combinations. But when the parameters T_m and $\text{FOM}(T_m)$ are chosen, the points of E combinations have considerably smaller deviations from the diagonal line, compared to those for P combinations. This means that the parameters T_m and $\text{FOM}(T_m)$ are more adequate than the parameters S_0 and h to characterize the process.

If we denote by Δ_v the difference between the values of a given parameter for the two materials of an E or P combination, where v = E, P, then the variance of this difference for the given parameter is

$$\mathrm{Var}(\Delta_v) = \langle \Delta_v^2 \rangle - \langle \Delta_v \rangle^2 = \sigma_v^2, \quad (v = \mathrm{E},\ \mathrm{P}). \tag{8}$$

The ratio of variances σ_E^2/σ_P^2 for E and P combinations was determined for different parameters. Results are shown in Tab. 4. The smallest value of σ_E^2/σ_P^2 is obtained for the parameter FOM(T_m).

Table 4. Ratio of variances σ_E^2/σ_P^2 of excellent and poor weldable dissimilar metal combinations for different parameters characterizing the thermal processings

Parameter	σ_E^2/σ_P^2
Melting temperature T_m	0.219
Specific processing energy $S_0 = c_p T_m$	0.358
Heat storage coefficient $h = K/\sqrt{\varkappa}$	0.608
$\mathrm{FOM}(T_m) = \rho c_p T_m$	0.197
$\mathrm{FOM}(T_a) = \rho c_p T_a,\ T_a = (T_m + T_v)/2$	0.311

We can conclude that the parameter FOM(T_{H0}) which is defined by Eq. (7) and has the meaning of a specific processing energy can be an adequate FOM function to characterize the laser thermal material processing.

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