Nekatere možnosti določitve rezalnih podatkov pri laserskem odrezovanju

Some Possibilities for Determining Cutting Data when using Laser Cutting

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Tehnološki problemi, s katerimi se srečujemo na področju uporabe strojev za lasersko odrezovanje, so posledica nezadostnega poznavanja laserske tehnike in pomanjkanja dovolj zanesljivih podatkov iz prakse in poznavanja parametrov, ki vplivajo na sam postopek odrezovanja. Pomemben parameter, ki ga moramo določiti in vključiti v programsko opremo številskega krmiljenja, je rezalna hitrost. Različni avtorji analizirajo postopek lasreskega odrezovanja in podajajo matematične modele, pri katerih je lasersko odrezovanje modelirano z rezalno hitrostjo, kot ključnim parametrom odrezovanja. Številčno vrednost rezalne hitrosti lahko določimo iz priporočil proizvajalca, z določenimi izkušnjami ali z uporabo enačb iz literature. V tem prispevku so predstavljene nekatere možnosti za določitev parametrov laserskega odrezovanja in rezalne hitrosti, na podlagi stopnje odrezovanja, ločilne energije in rabe specifične moči. © 2006 Strojniški vestnik. Vse pravice pridržane.
(Ključne besede: rezanje lasersko, hitrosti rezanja, parametri rezanja, podatki o rezanju)

The technological problems faced in the field of the application of laser-cutting machines lie in insufficient knowledge of the laser technique and the absence of both sufficiently reliable practical data and knowledge about the parameters affecting the work process itself. A significant parameter that is necessary to determine and to enter in an NC-program is the cutting speed. Various authors analyze the laser-cutting process and give mathematical models where laser cutting is modeled by using the cutting speed as the key cutting parameter. The numerical value of the cutting speed can be determined from the recommendations of manufacturers, a particular experience or with the aid of equations from the literature. This paper presents some possibilities for determining laser-cutting data and cutting speed based on cutting rate, severance energy, and the specific power consumption. © 2006 Journal of Mechanical Engineering. All rights reserved.
(Keywords: laser cutting, cutting speed, cutting parameters, data analysis)

0 INTRODUCTION

Laser technology is a very young technology, which has not even reached the age of 40 years. For a long time it has been a development searching for industrial applications. For most engineering applications, the laser can be regarded as a device for producing a finely controllable energy beam, which, in contact with a material, generates considerable heat. The heat energy is supplied by the laser beam. The laser beam permits tool-free machining with active heat energy. The energy of the light contained in the laser radiation is absorbed by the workpiece and transformed into thermal energy. The laser beam is becoming a very important engineering tool for cutting, welding and heat treatment.

Laser cutting (especially of mild steel) is a well-known and attractive process for cutting thin sheets. It is one of the most important applications for industrial lasers.

Laser cutting is a thermal, non-contact, mechanized process capable of cutting most materials with a high degree of precision and accuracy. Laser cutting is the process of melting or vaporizing material in a very small, well-defined area. The processes of heating, melting, and evaporation are produced by the laser beam, affecting a workpiece's surface. The desired cut is obtained by moving the laser beam along a given contour. The laser beam is a cutting tool that is able to cut all materials. A laser beam, focused into a very small spot of 0.1 to 0.2 mm in diameter, concentrates thousands of watts. The

power density for cutting steels is typically 10^5 to 10^6 MW/m². There is no other way to concentrate so much energy into such a small spot. The high power density of the focused laser beam in the spot melts or evaporates material in a fraction of a second. Since our desire is to remove the evaporated and molten material from the affected zone as soon as possible, the laser cutting is performed with a coaxial current of an assisting gas – gas-assisted laser cutting, Fig. 1. When cutting metals, gas-assisted laser cutting is normally applied. In gas-assisted laser cutting, the gas is usually introduced coaxially with the focused laser beam into the cutting area. The gas cools the cut area, thus reducing the heat-affected zone, and also removing the molten dross from the cut.

There are three different methods of cutting with a laser:
- sublimation cutting,
- fusion cutting,
- flame cutting.

In laser-sublimation cutting, the material is removed by evaporating the metal. This requires light densities obtainable by appropriate adjustment of the laser radiation and focusing, so that material removal occurs exclusively by means of evaporation. The metal vapour emitted is blown out of the cut by the cutting-gas jet. Generally, either argon or nitrogen is used in order to avoid oxidation of the cut edge.
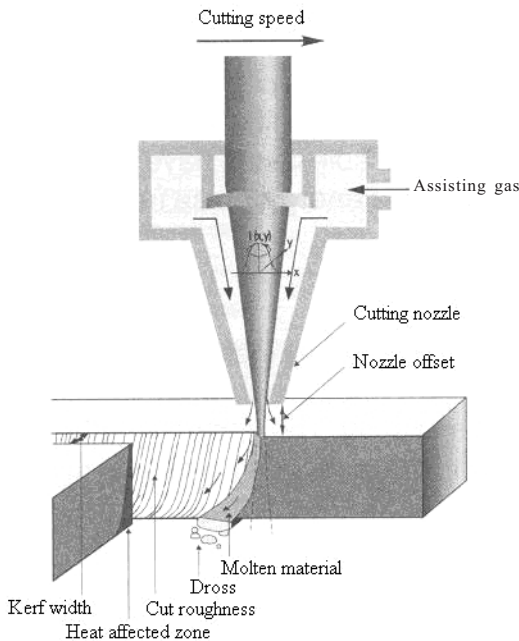
Since almost no melting occurs, smooth cuts can be obtained.

Laser fusion cutting requires less power than laser sublimation cutting as the material is only melted and then blown out of the cut with an inert-gas jet. With laser flame cutting, instead of an inert gas, pure oxygen is used. The material is heated beyond its ignition temperature until a highly exothermic reaction occurs, which supplies the energy for the cutting process. The liquid material is burned using the oxygen and blown downwards out of the cut by part of the assisting-gas jet. Laser-flame cutting and laser-fusion cutting are the predominant methods in the precision cutting of metals.

1 MELTING SPEED, EVAPORATING SPEED AND CUTTING SPEED

If the intensity of the laser-beam radiation is such that the temperature of the workpiece material for a small time attains the temperature of the melt or the evaporation then a small volume of material can be excluded from the cutting zone. After the temperature of melting or evaporation is achieved in the material a frontier layer is formed between the liquid and the hard phase or the gas phase and the liquid/hard phase. With a melt or evaporation of the layer of material thickness Δs the frontier layer moves in depth, while the laser beam makes a hole, i.e., perforates the material of the workpiece with a thickness s. Fig. 2 shows a model for determining the melting speed, the evaporating speed and the cutting speed.
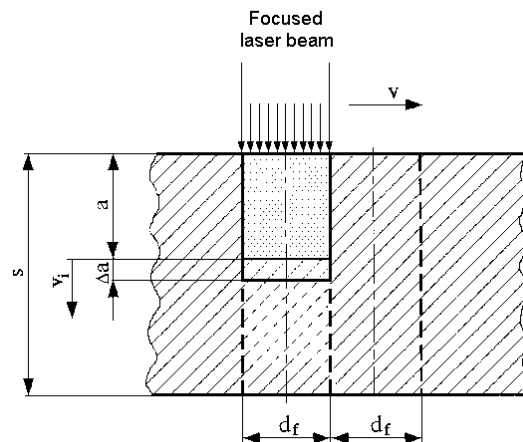

Fig. 1. *Gas assisting laser cutting*

Fig. 2. *Model for the determination of the cutting speed*

Radovanović M.

The melting speed can be estimated by employing a simple energy-balance arrangement. The principle is based on the fact that the material locally reaches the melt temperature because of the focused radiation.

The energy required to convert a mass m of a material in a cubic element (cylinder with base A_f and height s) at an initial temperature T_0 into a melt can be written with the equation:

$$E_m = m \left[C_S \left(T_m - T_0 \right) + L_m \right] \qquad (1),$$

where E_m (J) is the energy required to melt the material, m (kg) is the mass of material, C_S (J/kgK) is the solid specific heat capacity, T_m (K) is the melting temperature, T_0 (K) is the ambient temperature, and L_m (J/kg) is the latent heat of melting. We then use the following equation:

$$m = \rho V = \rho A_f s = \rho A_f v_m t = \rho \frac{\pi d_f^2}{4} v_m t \qquad (2),$$

where ρ (kg/m³) is the mass density, V (m³) is the cubic element (cylinder with base A_f and height s), A_f (m²) is the area of the laser spot, s (m) is the material thickness, v_m (m/s¹) is the melting speed, t (s) is the time, and d_f (m) is the focal spot diameter. We can put $C_S = C$, where C (J/kgK) is the specific heat capacity.

Thus, the equation of the energy balance is given by:

$$E_m = \frac{\pi d_f^2}{4} v_m t \rho \left[C \left(T_m - T_0 \right) + L_m \right] \qquad (3).$$

The power required to melt the material can be determined by the equation $P_m = \alpha P$, where P_m (W) is the power required to melt a material, α is the absorptive index, and P (W) is the laser power.

The absorption varies with the temperature for the metal surface and the CO_2 wavelength. The absorptive index at ambient temperature for steel is 0.1, at the melting temperature it is 0.55, and at the vaporization temperature it is 0.9 ([1] and [2]).

Since $E_m / t = P_m = \alpha P$ we can determine the melting speed in the form:

$$v_m = \frac{4 \alpha P}{\pi d_f^2 \rho \left[C \left(T_m - T_0 \right) + L_m \right]} \qquad (4).$$

The focused laser beam bores into the surface of the material with a velocity v_m, directed into the material. Using Equation (4) we can determine the cutting speed, providing that it does not include the effect of the assisting gas. If the focused laser beam has a diameter d_f and is being scanned at a velocity v, Figure 2, then the beam will traverse a distance equal to its diameter in a time $t = s/v_m$. During this time a cubic element of material V will be removed, and we have $t = s/v_m = d_f/v$.

The equation for determining the cutting speed is:

$$v = v_m \cdot \frac{d_f}{s} \qquad (5).$$

The theoretical equation for the cutting speed, in the event that the material is removed by melting, based on a balance of energy, is made with:

$$v = \frac{4 \alpha P}{\pi d_f s \rho \left[C \left(T_m - T_0 \right) + L_m \right]} \qquad (6),$$

where v (m/s) is the cutting speed.

From Equation (6) we can see that the cutting speed is linearly proportional to the laser power and inversely proportional to the sheet thickness. The cutting speed is small for materials with a high melting point and for materials with a high latent heat of melting. The cutting speed is also small for a large focal-spot diameter.

Based on Equation (6) we can determine the necessary energy for melting the material per unit area of the cut as:

$$E_{nm} = \frac{P}{vs} = \frac{\pi d_f \rho \left[C \left(T_m - T_0 \right) + L_m \right]}{4 \alpha} = const. \qquad (7),$$

where E_{nm} (MJ/m²) is the necessary energy for melting the material per unit area of the cut.

The necessary energy for melting the material per unit area of the cut is a constant value for the concrete material of the workpiece and the system for focusing the laser beam.

For mild steel ρ=7860 kg/m³, C=620 J/kgK, T_m=1515°C=1788K, T_0=20°C=293K, and L_m=247·10³ J/kg. For a focal-spot diameter d_f=0.2 mm and the absorptivity index at the melting temperature α=0.55 we have Equation (6) in the form:

$$v = 0.379 \frac{P}{s} \qquad (8)$$

and Equation (7) in the form

$$E_{nm} = \frac{P}{vs} = 2.63 \qquad (9).$$

Equations (8) and (9) include v(mm/s), P(W), s(mm) and E_{nm} (MJ/m²).

The evaporating speed can be estimated using the equal-energy method. The energy required to convert a mass m of a material cubic element at an initial temperature T_0 into a vapor can be written with the equation:

$$E_v = m\left[C_S\left(T_m - T_0\right) + C_L\left(T_v - T_m\right) + L_m + L_v \right] \quad (10),$$

where E_v (J) is the energy required to evaporate the material, C_L (J/kgK) is the liquid specific heat capacity, T_v (K) is the vaporization temperature, and L_v (J/kg) is the latent heat of vaporization.

Usually, $L_v >> L_m$ and $T_v >> T_0$ and we assume we can put $C_S \approx C_L = C$. Thus, the equation of energy balance (10) is given by:

$$E_v = m\left(CT_v + L_v \right) \quad (11).$$

Since $m = \rho \dfrac{\pi d_f^2}{4} v_v t$, where v_v (m/s) is the evaporating speed, we have:

$$E_v = \frac{\pi d_f^2}{4} v_v t \rho \left(CT_v + L_v \right) \quad (12).$$

The power required to evaporate the material can be determined by the equation $P_v = \alpha P$, where P_v (W) is the power required to evaporate the material.

Since $E_v / t = P_v = \alpha P$ we can determine the evaporation speed in the form:

$$v_v = \frac{4\alpha P}{\pi d_f^2 \rho \left(CT_v + L_v \right)} \quad (13).$$

A focused laser beam boring into the surface of a material with a velocity v_v directed into the material.

Using Equation (13) we can determine the cutting speed, providing that the effect of the assisting gas is not included.

If the focused laser beam has a diameter d_f and is being scanned at a velocity v, Figure 2, then the beam will traverse a distance equal to its diameter in a time $t = s/v_v$. During this time a cubic element of material V will be removed, and we have $t = s/v_v = d_f/v$.

The equation for determining the cutting speed is:

$$v = v_v \cdot \frac{d_f}{s} \quad (14).$$

The theoretical equation for the cutting speed, in the event that the material is removed by vaporization, based on the balance of energy is carried out with:

$$v = \frac{4\alpha P}{\pi d_f s \rho \left(CT_v + L_v \right)} \quad (15),$$

where v (m/s) is the cutting speed.

Equations (6) and (15) are theoretical, and do not include the influence of the assist gas, especially if it is oxygen. With laser oxygen cutting the oxidation reaction generates heat, which accelerates the cutting process. It contributes approximately 40% of the energy required for the cutting.

The necessary energy for the vaporization of material per unit area of cut is:

$$E_{nv} = \frac{P}{vs} = \frac{\pi d_f \rho \left(CT_v + L_v \right)}{4\alpha} = const. \quad (16),$$

where E_{nv} (MJ/m^2) is the necessary energy for the vaporization of material per unit area of cut.

For mild steel T_v=3160 K and L_v=6.8·10^6 J/kg. For the focal spot diameter d_f=0.2 mm and the absorptivity index at the vaporization temperature α=0.9 we have Equation (15) in the form:

$$v = 0.083 \frac{P}{s} \quad (17).$$

And Equation (16) in the form:

$$E_{nv} = \frac{P}{vs} = 12.08 \quad (18).$$

In Equations (17) and (18) we have v(m/s), P(W), s(mm) and E_{nv}(MJ/m^2).

We can determine the severance energy (the energy necessary for cutting the material per unit area of cut) as:

$$E_s = \frac{P}{vs} \quad (19),$$

where E_s (MJ/m^2) is the severance energy.

The value of the severance energy is essentially a quantitative measure of the difficulty of cutting: the larger the value, the more difficult a material is to cut. It is evident that the severance energy E_s is between the energy necessary for melting the material E_{nm} and the energy necessary for the vaporization of the material E_{nv}:

$$E_{nm} < E_s < E_{nv} \quad (20).$$

The theoretical range of values for the severance energy, E_{st}, for mild steel is:

$$2.63 < E_{st} < 12.08 \qquad (21),$$

where E_{st} (MJ/m^2) is the theoretical value of the severance energy.

2 DETERMINATION OF THE CUTTING DATA

The process of laser cutting can be described by the following characteristics: cutting rate, severance energy, and specific power consumption.

The cutting rate is defined by the equation:

$$R = v \cdot s \qquad (22),$$

where R is the cutting rate, v is the cutting speed, and s is the material thickness.

The severance energy is defined by the equation:

$$E = \frac{P}{v \cdot s} \qquad (23),$$

where E is the severance energy, P is the laser power, v is the cutting speed, and s is the material thickness.

The specific power consumption is defined by the equation:

$$P_s = \frac{P}{Q} \qquad (24),$$

where P_s is the specific power consumption, P is the laser power, and Q is the material removal rate.

Tables 1 and 2 contain the numerical values of the cutting rate, the severance energy, and the specific power consumption for the laser oxygen cutting and laser nitrogen cutting of mild steel. The values of the parameters are variable and change with the lens, the focal point stand-off, the nozzle diameter, the nozzle stand-off, and the assisting-gas pressure. All the parameters are the middle values, calculated on the basis of cutting data from manufacturers ([10] and [11]).

Between the cutting rate, R, and the severance energy, E, we have a dependence in the form:

$$R \cdot E = P \qquad (25),$$

where P is the laser power.

Between the cutting rate, R, and the specific power consumption, P_s, we have a dependence in the form:

$$R \cdot P_s = \frac{P}{s_r} \qquad (26),$$

where P is the laser power, s_r is the cut width.

Between the severance energy, E, and the specific power consumption, P_s, we have a dependence in the form:

Table 1. *Cutting data for laser oxygen cutting*

Characteristics	Laser power		
	1000 W	2000 W	3000 W
Cutting rate R(m^2/s)	$(12 \div 16)10^{-5}$	$(20 \div 25)10^{-5}$	$(23 \div 33)10^{-5}$
Severance energy E(MJ/m^2)	$6 \div 8$	$8 \div 10$	$9 \div 13$
Specific power consumption P_s(GJ/m^3)	$21 \div 33$	$23 \div 42$	$25 \div 54$
Material: mild steel; assisting gas: oxygen			

Table 2. *Cutting data for laser nitrogen cutting*

Characteristics	Laser power		
	1000 W	2000 W	3000 W
Cutting rate R(m^2/s)	$(8.5 \div 12)10^{-5}$	$(17 \div 20)10^{-5}$	$(17 \div 25)10^{-5}$
Severance energy E(MJ/m^2)	$8.5 \div 12$	$10 \div 12$	$12 \div 18$
Specific power consumption P_s(GJ/m^3)	$54 \div 72$	$60 \div 72$	$60 \div 90$
Material: mild steel; assisting gas: nitrogen			

$$\frac{E}{P_s} = s_r \quad (27),$$

where s_r is the cut width.

With these characteristics we can determine the principal parameters of the laser-cutting process.

2.1 Determining the cutting data using the cutting rate

On the basis of the cutting rate, R, we can estimate:

- cutting speed, v:

$$v = \frac{R}{s} \quad (28),$$

- material removal rate, Q:

$$Q = v \cdot s \cdot s_r = R \cdot s_r \quad (29),$$

- time to make the cut, t_g:

$$t_g = \frac{\ell}{v} = \frac{V}{Q} \quad (30),$$

Example 1: Laser, oxygen cutting; laser, 1000W; material of workpiece, mild steel; material thickness, 4mm; and length of cut, 1m.

For the laser of 1000W, from Table 1 we have a middle value of the cutting rate $R=14\cdot10^{-5}$m²/s. For the cut width we take $s_r=0.25$mm,
for the volume of removed material, $V=1.0$cm³,
for the cutting speed, $v=0.035$m/s,
for the material removal rate, $Q=3.5\cdot10^{-8}$m³/s,
and for the cutting time, $t_g=28.57$s.

2.2 Determining the cutting speed with the severance energy

On the basis of the severance energy, E, according to Equation (23), we can estimate the cutting speed v as:

$$v = \frac{P}{E \cdot s} \quad (31).$$

Example 2: Laser, oxygen cutting; laser, 1000W; material of workpiece, mild steel; and material thickness, 4mm.

For a laser of 1000W, from Table 1 we have a middle value of the severance energy $E=7$MJ/m². Cutting speed, $v=0.035$m/s

2.3 Determination of the cutting speed by specific power consumption

On the basis of the specific power consumption, P_s, according Equations (24) and (29),

we can estimate the cutting speed v as:

$$v = \frac{P}{P_s \cdot s \cdot s_r} \quad (32).$$

Example 3: Laser, oxygen cutting; laser, 1000W; material of workpiece, mild steel, and material thickness, 4mm.

For a laser of 1000W, from Table 1 we have a middle value of the specific power consumption of $P_s=27$MJ/m³. For the cut width we take $s_r=0.25$mm. Cutting speed, $v=0.037$m/s

2.4 Determination of the cut width by cutting rate and specific power consumption

On the basis of the cutting rate, R, and the specific power consumption, P_s, we can estimate the cut width s_r as:

$$s_r = \frac{P}{R \cdot P_s} \quad (33).$$

Example 4: Laser, oxygen cutting; laser, 1000W; and material of workpiece, mild steel.

For a laser of 1000W, from Table 1 we have middle values of the cutting rate $R=14\cdot10^{-5}$m²/s, and a specific power consumption $P_s=27$GJ/m³. Cut width, $s_r=0.26$mm

2.5 Determination of the cut width by the severance energy and specific power consumption

On the basis of the severance energy, E, and the specific power consumption, P_s, according to Equations (25) and (26) we can estimate the cut width s_r as:

$$s_r = \frac{E}{P_s} \quad (34).$$

Example 5: Laser, oxygen cutting; laser, 1000W; and material of workpiece, mild steel.

For a laser of 1000W, from Table 1, we have middle values of the severance energy $E=7$MJ/m², and specific power consumption $P_s=27$GJ/m³. Cut width, $s_r=0.26$mm

3 DETERMINATION OF THE CUTTING SPEED BASED ON EXPERIMENTS

The experiments were performed on a CO_2 laser-cutting machine with computer numerical control. The technical characteristics of the CO_2 laser

are: radiation wavelength, 10.6μm; zone of the continual laser power control, 0.2 to 1.3kW; continual work regime; beam divergence less than 4 mrad; mode TEM_{00}; and circular polarization. The optimal laser power is 0.8kW. The focusing system lens is 28mm in diameter and a focal distance of 125mm. The nozzle con opening is 1.6 mm. The material used for the examination is steel Ust 13 (DIN). The work process is carried out using the oxygen process with 99.8% purity.

The experimental equation for the cutting speed is obtained with the aid of a factorial plan of experiments and with ([5] and [8]):

$$v = 0.379 \frac{P^{0.78} h_s^{0.59}}{s^{0.91}} \qquad (35),$$

where v (m/s) is the cutting speed, P (kW) is the laser power, h_s (mm) is the dross height, and s (mm) is the material thickness.

Equation (38) can be rearranged to give:

$$\frac{P}{v} = 2.64 \frac{P^{0.22} s^{0.91}}{h_s^{0.59}} \qquad (36).$$

The experimental range of values of the severance energy is:

$$E_{se} = \frac{P}{vs} = 2.64 \frac{P^{0.22}}{s^{0.09} h_s^{0.59}} \qquad (37),$$

where E_{se} (MJ/m²) is the experimental value of the severance energy.

In Equations (36) and (37) we have P/v (kJ/m) and P/vs (MJ/m²).

The tentatively derived Equations (36) and (37) model the interrelation between the cutting speed, the laser power, the material thickness, and the dross height for the laser oxygen-cutting of mild steel.
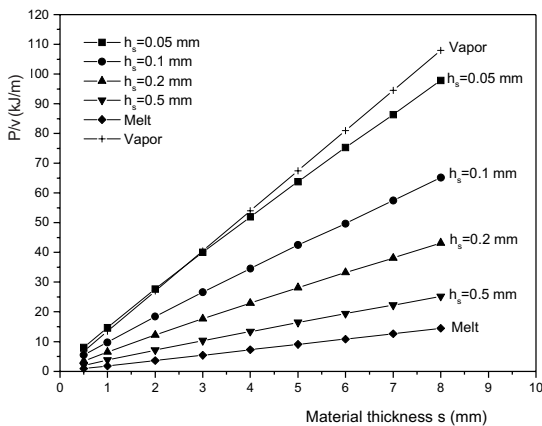
The experimental range of values of the severance energy for mild steel is:

$$2 \text{ MJ/m}^2 < E_{se} < 13 \text{ MJ/m}^2 \qquad (38).$$

The value E_{se} includes the influence of the reactive gas on the laser-cutting process.

Fig. 3 and Fig. 4 show P/v and $P/(vs)$ against s for various dross heights, molten and evaporated material. From Figure 3 we can see that the relationship between the laser power/cutting speed P/v and the material thickness s is linear. The field of cutting is between the line of melting and the line of vaporization. In this case dependence is a function of the dross height. From Figure 4 we can see that the relationship between the laser power/(cutting speed and material thickness) $P/(vs)$ and the material thickness s is approximately constant. This means that the severance energy E_{se}, or $P/(vs)$, has a constant value for the concrete material of the workpiece. The required severance energy, E_{se}, is between the energy for melting and the energy for the vaporization of the material.

4 CONCLUSION

The technological problems related to the application of the laser-cutting process are an insufficient knowledge of the application of the laser technique as well as an absence of sufficiently reliable practical data and knowledge about the parameters influencing the work process itself. High levels of contour precision at a precisely defined cutting speed have an important effect on the quality of the cut. Therefore, in order to contribute to practical data, this paper gives the results of both the theoretical and the experimental research,
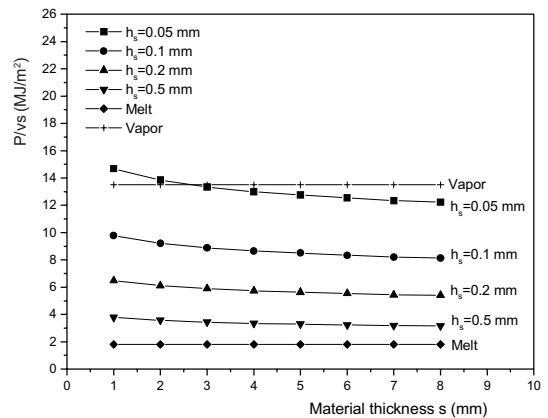

Fig. 3. P/v vs. s

Fig. 4. $P/(vs)$ vs. s

referring to the determination of the principal parameters by laser cutting. The cutting data of the laser cutting can be described by the cutting rate, the severance energy, and the specific power consumption. The theoretical range of values for the severance energy is $2.63\,\text{MJ/m}^2 < E_{st} < 12.08\,\text{MJ/m}^2$, and the experimental range of values is $2\,\text{MJ/m}^2 < E_{se} < 13\,\text{MJ/m}^2$. The value of E_{se} is essentially a quantitative measure of the cutting difficulty: the larger the value, the more difficult a material is to cut. The value E_{se} includes the influence of the reactive gas on the laser-cutting process. For a determination of the cutting data, as useful initial data it is useful to take the mean values from Table 1 and 2 for the laser cutting of mild steel. Using these values an operator of a laser cutting machine can rapidly estimate the kind of cutting speed for a given thickness of material and the optimal laser power.

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