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Laser cutting of an AlSi alloy/SiC$_p$ composites: theory and experiments

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ABSTRACT

Purpose: Discontinuous silicon carbide reinforced aluminium alloy metal matrix composites have proved to be extremely to cutting using conventional cutting tools. Thus, there is a need to introduce new processing method in order to improve both the working conditions and the quality of the products made of metal matrix composites. Laser processing offer the advantages of high processing rates, no tool wear, no contact forces, and relatively high precision. Currently the mechanisms governing the laser cutting process of composites are not fully understood. It is the aim of the authors therefore to investigate the physical processes of laser composite material interactions and the phenomena occurring within the cutting front, viz. the formation of striations, and the effect they have on the resulting cutting quality.

Design/methodology/approach: The analysis has taken into the consideration these AlSi alloy/SiC$_p$ composites are heterogeneous structural material consisting of two components: a semiconductor and metal alloy that have two different optical absorptions mechanisms to laser radiation. The mathematical model based on energy and mass balance model was used to calculate the maximum cutting depth for fixed cutting speed and laser beam power.

Findings: Results indicated that the change in absorptivity magnitude about 0.1 led to a strong increase in power of laser energy absorbed per unit depth in AlSi alloy/SiC$_p$ composites.

Research limitations/implications: In mathematical modeling the constant values of the effective absorptive parameter describing the energy input from laser to composite and a constant thermophysical properties of composite components are used. During the laser beam scanning the absorptive of the composite surface may changes.

Practical implications: The proposed mathematical model is in good agreement with the experimental data obtained for a CO$_2$ laser cut of AlSi alloy/SiC$_p$ composites. It is important to understand the characteristics of the striation so that the laser cutting process of composite can be optimized.

Originality/value: The cut kerf characteristics such as the dross formation, the heat affected zone in terms of laser parameters process was investigated.

Keywords: Composites; Heat treatment; Laser beam interactions; Laser modeling

1. Introduction

Discontinous silicon carbide reinforced aluminium alloy metal matrix composites (AlSi-alloy/SiC$_p$) have been under development for many years, and commercially available in significant quantities for the last decade. This is because SiC has advantages over other ceramic reinforcements such as thermal conductivity, density, relative cost, corrosion resistance. Addition of moderate volume fraction of SiC to aluminium alloy only results in a slight increase in density because the two components have similar density. Thus, the AlSi-alloy/SiC$_p$ composites can directly replace the aluminium alloy without significant increase in weight of the structural components [1]. However, one of the major problems preventing widespread engineering applications of AlSi-alloy/SiC$_p$ composite are high manufacturing costs associated with the difficulties experienced in machining of these materials. The reinforced phase of AlSi-alloy/SiC$_p$ composites is hard and abrasive: SiC$_p$ particles are harder than conventional cutting tools such as high speed steel and common cemented carbide. With the conventional tool materials tested for the AlSi-alloy/SiC$_p$ machining, actually only diamond cutting tools are proper [2]. The diamond cutting tools based on natural, policrystaline or CVD diamond are considered right but expensive. Then, alternative material removal methods of AlSi-alloy/SiC$_p$ machining such as Electro Discharge Machining, Abrasive Water Jet and laser technique increasingly being used for the machining of AlSi-alloy/SiC$_p$ composite [3,4]. Laser processing offer the advantages of high processing rates, no tool wear, no contact forces, and relatively high precision. However, since the different kind of AlSi-alloy/SiC$_p$ reveal a wide range of optical, thermophycical properties [5] laser processing parameters have to be adapted individually to accomplish the laser cut with an optimum quality. The present paper analyzes the physical mechanisms of the optical absorption occurred during interaction of laser beam with the AlSi-alloy/SiC$_p$. The theoretical results obtained from the physical model describing the laser cutting are compared with the experimental result of nitrogen assisted CO$_2$ laser cutting of the AlSi-alloy/SiC$_p$.

2. Physical formulation of the laser beam interaction with AlSi-alloy/SiCp

The effectiveness of laser beam interactions with composite during laser cutting depends primarily on the optical and thermal properties of the AlSi-alloy/SiC$_p$ composite materials as well as the laser process parameters. The electromagnetic radiation emitted by high power lasers machine used for industrial processing can be focused to a spot with micrometer order diameter. When we compare the size of the laser focused beam and the size of the SiC$_p$ particle in composite materials [4] we can come to the conclusion that the laser beam during scanning interact alone with the SiC$_p$ particles and AlSi-alloy metal matrix. From physical point of view, these materials have different absorption mechanisms of electromagnetic radiation: The Silicon Carbide reinforcement (β–SiC) particles are wide-gap semiconductor materials with band gap energy $E_g \cong 3.2$ eV. Photons emitted by CO$_2$, Nd:YAG and even High Power Diode Laser (HPDL) so-called semiconductor laser have energy smaller than E_g of β–SiC materials, so the effective interband transitions mechanism absorption do not occur. In this case, the photons with energy smaller than E_g could be absorbed in SiC mainly by the multhiphtonon absorption mechanism [6]. The metal matrix (AlSi-alloy) absorb the laser energy mainly by the electrons: photons emitted by CO$_2$, Nd:YAG and HPDL lasers are absorbed by the free electrons in conduction band of AlSi-alloy. The kinetic energy of free electrons excited by photons are next transmitted through collision to the crystalline lattice of the AlSi-alloy.

The photons emitted by laser are absorbed in the material depth proportional to $1/\alpha$ called the absorption depth. For AlSi-alloy/SiC$_p$ composite the components absorption depth are $1/\alpha_{SiC} = 0{,}68\ \mu m$ and $1/\alpha_{AlSi\text{-}alloy} = 0{,}03\ \mu m$ respectively for wavelength radiation $\lambda = 10{,}6\ \mu m$. This means that at first steep of laser interactions with composite materials, the absorbed laser energy heated only a thin solid surface of AlSi-alloy/SiC$_p$ material. Using one-dimensional heat conduction equation with the condition no phase transitions occurs, the surface temperature time dependence could be estimated by equation [7];

$$T(t) = T_0 + (I_0 A / K\alpha)\left[2\alpha\sqrt{\kappa t/\pi} + \exp(\alpha^2 \kappa t)\, erfc(\alpha\sqrt{\kappa t}) - 1\right] \quad (1)$$

where: Io [W/m^2] is the laser radiation intensity at the material surface, and physical materials properties such as: α [1/m] – the absorption coefficient, A –the surface absorptivity, K - the thermal conductivity, κ $(=K/c_p\rho)$ – thermal diffusivity, c_p- specific heat at constant pressure, ρ – mass density. The material properties A, K, c_p, ρ, generally temperature depend but in this calculations the averages values of material properties accepted. For calculations with equation (1), the average thermal conductivity values between room temperature and boiling temperature for SiC$_p$ and for AlSi-alloy materials are used. Obtained from above equation the time evolution of the surface temperature variation rate for AlSi-alloy and SiC$_p$ materials were plotted in Fig.1.

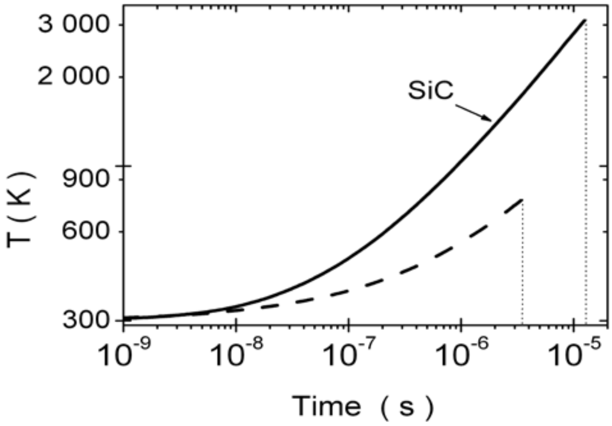

Fig. 1. Time dependence of the surface temperature in SiC (solid line) and AlSi-alloy (dashed line) irradiated by a CO$_2$ laser beam of laser radiation intensity 10^7 (W/cm^2), plotted from Eq.(1)

It could be seen (Fig. 1) the exponential growth of the surfaces temperature for both components at a larger time of laser beam interaction and that the melting temperature 850K for AlSi-alloy material could be reached after 5 μs time whereas for SiC$_p$ particle the sublimation temperature T_m=3103 K, after t=12 μs. These results indicate that the melting time of the AlSi-alloy metal matrix is almost two times shorter than for SiC$_p$ particle at the same laser radiation intensity.

When laser beam is irradiated on a AlSi-alloy/SiC$_p$ material surface, a portion of laser energy is absorbed and next conducted into the interior of the material. If the absorbed energy is high enough, material surface will melt and the melting front will propagate into the workpiece. Boiling and vaporization can also occur at the free surface of the melt. For AlSi-alloy/SiC$_p$ the melting heat of the components is much smaller than the evaporation heat of ones. Therefore, a more economical method, which does not require high laser power is gas-assisted laser cutting, in which the composite material is locally (within the spot of focused laser radiation) heated to the melting point (particularly the low-melting AlSi-alloy matrix) and next is entrained due to intense blowing of the assisted gas jet.

To make use of the principle energy and mass balance it would be possible to describe the amount of the essential laser energy to melted unit depth of composite material. The overall energy balance equation for laser radiation takes the form [8, 9]:

$$E_i = E_{Tm} + E_{Lm} + E_{Lb} + E_{Tl} + E_d + E_{loss} \qquad (2)$$

where: E_i – laser energy supplied to the interaction (cut) zone, E_{Tm} – energy required to rise the solid substrate of composite material from room temperature to melting temperature, E_{Lm} – latent heat of melting, E_{Lb} - latent heat of boiling, E_{Tl} - energy required to raise the temperature of the liquid substrate beyond T_m, E_d – energy loss as a result of the splashing of molten droplets by the assist gas and the sticking of molten layers to the side walls of the kerf, E_{loss} is the energy loss from the melt to the surrounding solid region in the composite materials and due to heat conduction and convective heat loss from the melt to the assist gas at the free surface of the liquid material.

3. Experiments

AlSi-alloy/SiC_p composite used in this study were fabricated using stir casting method (liquid-phase processes). The metal matrix were aluminium alloy containing (in wt%): Si-12, Cu-1.1, Mg-0.5, Ni-0.95. Al-(bal.). The composites have been obtained by introducing the SiCp ceramic particles as reinforcement into the mixed liquid metal matrix [10]. The average particle of SiC_p was about 50μm. Specimens of AlSi-alloy/SiC_p with size 150 x 80mm and thickness from 3 to 15 mm were prepared for laser cutting. The surfaces were ground with 600 grit SiC paper and cleaned with methanol prior to the laser cutting.

In the present work the laser cutting experiments were performed by means of an Trumpf TLF4000 turbo carbon dioxide laser delivering a maximum output power of 4 kW at a wavelength of 10.6 μm, operating in pulsed mode and a continuous 1.8 kW CO_2 Spectra-Physics 820. The laser beam was focused on the upper surface of the AlSi-alloy/SiC_p specimens. The lens system used to focus the laser beam onto the specimens consisted in a ZnSe lens with a focal length of 127 mm. The laser beam, together with the coaxial assisting gases, passes through a conical cutting nozzle with an aperture of 1.5 mm. The cutting gas used was nitrogen; the range of nitrogen pressure was 10-16 bar. The microstructure and geometrical characteristics of the laser cuts were measured by means of an Olympus optical microscope GX71 and contact instruments Surtronic3+, Taylor-Hobson for the surface roughness measurements.

Figure 2 shows obtained from equation (2) and prediction proposed by Kar at all. [8, 9] the theoretical dependency of CO_2 laser energy absorbed per unit depth *(P/d)* in AlSi-alloy/SiC_p composite material as a function of the cutting speed velocity. Three different absorptivity (A =1-R) values in range of 0,17 to 0,3 were used for theoretical calculations. Theoretical curves in Fig. 2 show that the power of laser energy absorbed per unit depth (P/d) in AlSi-alloy/SiC_p increases almost linearly as the scanning laser velocity increases. It has been found that the P/d parameters are sensitive to the exact value of the absorptivity, especially for high cutting speed. The change in value of absorptivity magnitudes about 0.1 led to strong increases in P/d parameters. The theoretical curve closely follows the experimental CO_2 laser cutting data obtained for AlSi-alloy/SiC_p and validates the used model. The better conformity between theoretical and experimental results are observed for constant value A=0,2 of the absorptivity. This parameter used from experimental investigations is effective absorptive parameter [5] but locally during laser scanning through the surface, absorptivity value of AlSi-alloy/SiC_p composite may change. It would be emphasize that the calculated from energy balance models results are maximum obtainable cutting depth for fixed maximum cutting speed and average CO_2 laser beam power.

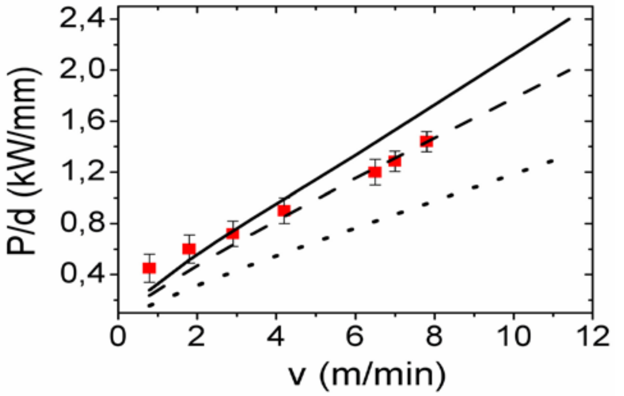

Fig. 2. Power of laser beam per unit depth of AlSi-alloy/SiC_p 15vol.% composite as a function of the cutting speed velocity calculated for three different absorptivity values. (A=0,17 - solid line; A=0,2 - dashed line; A=0,3 - dotted line; symbol ■ - indicate the experimental results obtained for CO_2 laser cutting with nitrogen assist gas)

In the gas-assisted laser cutting technique important as the optical and thermo-physical properties of material are also laser machining parameters [11]: e.g: -the average laser beam power, frequency and duty cycle, -velocity of the cutting process; -the nozzle shape as well as the pressure of the assisted gas; -distance from bottom of nozzle tip the top of the material (stand-off distance); -the focal position of the laser beam. In practice, usually the combination of these parameters allows to achieve the high quality and efficiency laser cutting process of the AlSi-alloy/SiC_p composite.

To verify the gas jet effects on the laser cut quality the cutting have been carried out under the same conditions, (machining parameters) for AlSi-alloy/SiC_p composite as well as for AlSi-alloy metal matrix comparative specimen. The typical example of the CO_2 laser cutting of the AlSi-alloy/SiC_p composite materials with supersonic jet of nitrogen used as an assist gas was shown at Fig. 3. The obtained kerfs for AlSi-alloy/SiC_p show good parallelism, and the kerf width varies no more than ±0.5mm for 8 mm thick cutting plates. For AlSi-alloy/SiC_p cut surface edge has a random roughness – striations [12, 13]. The surface roughness Ra (root-mean-square average) of the middle part of the cut surfaces was Ra=(17,1±3,4) μm for AlSi-alloy/SiC_p 15vol.% and for AlSi-alloy Ra=(2,9±0,8) μm. The other results with Ra were obtained by Müller and Monaghan [14] but for thinner AlSi-alloy/SiC_p composite workpiece.

The most common problem associated with laser cutting of thick plate of AlSi-alloy/SiC_p is the presence of adherent dross along the bottom cut edge, Fig. 3. This is because the proportion of the liquid AlSi-alloy/SiC_p is ejected from the cut zone, but, owing to the high surface tension, the gas jet can not remove completely all the melt [15]. The distinctive cut edge generated by the laser cutting process is covered in rapidly solidified melt, which often shows signs of turbulent flow during solidification in the lower part of the cutting (Fig.3). As predicted by the theoretical model, the changes of about 10% in absorptivity value of AlSi-alloy/SiC$_p$ have had a strong influence on the laser cutting process. Because the optical absorptivity of AlSi-alloy/SiC$_p$ materials changes during laser scanning, this cause additional fluctuations in the laser cutting front. These changes of laser interaction cause even local overheating of the AlSi-alloy/SiC$_p$ which manifests itself in plasma scintillation observed during the CO$_2$ laser cutting process.

Fig. 3. Typical example of cut edge of the 8 mm thick AlSi-alloy/SiC$_p$ 15vol.% composite specimen cutting with laser; cutting parameters: average power of CO$_2$ laser P=4 kW, pulse repetition rate f =10 kHz, nitrogen jet assistance gas pressure 16 bar, nozzle-material standoff distance 2 mm.

Apart form the perpendicularity of the cut edge, and surface roughness, the size of heat affected zone (HAZ) was also examined for the laser cutting quality of AlSi-alloy/SiC$_p$. At the top part of the cut edge the SiC$_p$ particles were not melted during the laser cutting. The full size SiC$_p$ particles are close to the laser cutting surface, and present along the whole length of the cut edge. Also, not micro segregation process or inhomogeneous distribution of SiC$_p$ (compared to non heat treated AlSi-alloy/SiC$_p$ microstructure) are observed in this area. There is no additional pores or voids in laser treated area. The HAZ width of the top cut edge could be estimated at 50 µm. The average HAZ width of the middle cut edge could be estimated at 400 µm.

4. Conclusions

The laser beam interaction with AlSi-alloy/SiC$_p$ composites is complex because the laser beam interacts “almost at once” with many components of AlSi-alloy/SiC$_p$ composites, characterized by different physical properties. The differences in optical absorption in laser radiation as well as the differences in thermal conductivity values of AlSi-alloy/SiC$_p$ composites components causes that during interaction with laser beam the components are heated and melted at different time and different quantity. The presented results of the interaction high intensity laser radiation with the AlSi-alloy/SiC$_p$ composites material indicated that the melting time of the AlSi-alloy metal matrix is almost two times shorter than for SiC$_p$ particle. It could be important for laser processing AlSi-alloy/SiC$_p$ because the taking appropriates parameters such as: laser power, beam frequency and duty cycle and the beam scanning speed it would be possible to influence on the temperature range in the melted zone. Hence the rate of chemical reaction between AlSi-alloy/SiC$_p$ composite materials atoms could be controlled.

There are varieties of factors involved in laser cutting of AlSi-alloy/SiC$_p$; such as the temperature of the molten material to form a layer, kinetic viscosity coefficient and its temperature gradient in molten layer, surface tension, gas flow rate and velocity, geometry of the cutting front. Purely physical description such as energy and mass balance can not fully describe all these complex physical phenomena which are observed during laser cutting of the AlSi-alloy/SiC$_p$ composites with the assist gas. Especially the mechanism of striation or dross formation in laser cutting process is not particularly clear.

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