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Research Paper

Diameter prediction of removal particles in Al_2O_3 ceramic laser cutting based on vapor-to-melt ratio

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ABSTRACT

In order to predict the particle size of molten removal in laser cutting Al_2O_3 ceramic plate, an atomization model based on vapor-to-melt ratio is developed to reveal the relationship between material remove forms and results during the process of vaporization-melt. Model correction of vapor-to-melt ratio with different parameters is obtained by laser cutting of 96.4% Al_2O_3 ceramic plate to get the slit width. The experimental verification is carried out on a JK701H Nd:YAG pulse laser cutting system by simulating under the regression correction of melt flow diameter. Micro-observation on the molten particles with different plate thickness (1.5 mm, 2.0 mm, 3.0 mm varied with increasing of vapor-to-melt ratio) and the calculations show that the particle diameter decreases rapidly (70 μm, 60 μm, 35 μm) with vapor-to-melt ratio after increasing to an extreme value (80 ~ 85 μm). It is proved that there is an antagonistic relationship between kinetic and thermodynamic effect in the impact of vapor-to-melt ratio (with critical value of 0.1) on the morphology of cutting removal. The results show good agreement between atomization model and experiments with average error below 8%. The analysis verifies this model is feasible and it makes contribution to determine the reasonable processing parameters (such as the control of vapor-to-melt ratio) in laser precision cutting.

1. Introduction

During the process of laser cutting Al_2O_3 ceramics, the material soften into the molten layer because of the surface temperature of plate increasing rapidly with the energy absorption. One part of the material is vaporized by energy absorption, while the other part blown away from substrate by assistant gas as the form of molten droplets. These molten materials are stretch-broken, quickly cooled and solidified into spherical particles to complete the removal process. As a decisive factor of removal form, vapor-to-melt ratio proposed by Luo et al. (2016) revealed the relationship between the processing parameters and the cutting quality, which represent the influence of melting and vaporizing ratio on cutting effects. At the same time, the shape of molten particles can also be used as one of the important criteria of cutting quality under the control of vapor-to-melt ratio to provide experimental evidence in laser cutting Al_2O_3 ceramics. Lawley (1977) reported that, the melting removal process of laser cutting Al_2O_3 ceramic is the same as that of the typical atomization cooling process from the gas-liquid relationship, action area state, cooling mode, removal form, etc. The basic principle is that the molten material stream (i.e. the molten layer) meets at a certain point with a converging high velocity gas steam (argon or nitrogen) from the assistant gas nozzle and is broken into fine molten droplets, which are spherized by surface tension and rapidly cooled to form Al_2O_3 ceramic powder. The size, shape and composition of particles are influenced by the state of gas and liquid flow, leading to a respectively wide diameter range (20 ~ 200 μm).

Scholars have carried out a series of studies along with the in-depth understanding of the cutting and atomization process. The cutting of alumina ceramics is a significant technological challenge because of these materials' typical high mechanical strength and thermal resistance. Li and Sheng (1995) presented a study of fracture initiation in thin alumina ceramics. The results showed that avoidance of fracture initiation results from a high energy density cutting condition. Wee et al. (2008) reported a statistical analysis of striation formation during laser cutting of ceramics. It was found that the striation wavelength is influenced by interaction time and irradiance. Yilbas et al. (2013) predicted the thermal and residual stress by numerically using ABAQUS finite element code. Oosterbeek et al. (2016) optimized the focal length and depth, power, speed, and number of passes to achieve fast and accurate cutting of technical ceramics by using femtosecond pulses. The overall processing speed was more than 4 times faster than previously achieved using fs laser ablation. In terms of atomization, Zhang et al. (2011) illustrated the preparation of white alumina spherical composite magnetic abrasive by gas atomization and rapid solidification. Ünal

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Nomenclature

d_m	Particle diameter, μm
d_0	Melt flow diameter (slit width), μm
m_l	Mass flow rate of liquid, g s^{-1}
m_g	Mass flow rate of gas, g s^{-1}
ρ_g	Gas density at atomization pressure, g cm^{-3}
ρ_m	Melt density at melting point, g cm^{-3}
v_g	Velocity of assistant gas, m s^{-1}
v_m	Velocity of molten material, m s^{-1}
g	Gravitational acceleration, m s^{-2}
p	Atomizing pressure, MPa
p_0	Pressure at the back pressure section, MPa
Δh	Height of the section, mm
C	Constant value
γ	Adiabatic index of assistant gas
S	Cross-sectional area at the nozzle outlet, mm^2
A	Cross-sectional area of melt flow, mm^2
U	Internal energy, J
β	Kinetic energy factor
h	Hydrostatic height of the fluid, mm
Q	Heat of the melt, J
σ_m	Surface tension of molten material, 10^{-3}N m^{-1}
C_D	Melt release coefficient
Δp	Difference between the upper and lower surface pressure of the material, MPa
ν_g	Kinetic viscosity of molten material, Pa s
ν_m	Kinetic viscosity of assistant gas, Pa s
K	Atomization constant
r_{vmr}	Vapor-to-melt ratio
m_v	Amount of vaporization, g (equivalent to vaporization flow rate, g s-1)
m_m	Amount of melting, g (equivalent to melting flow rate and removal, g s-1)
m_0	Weights of whole device before processing, g
m_1	Weights of whole device after processing, g
m_2	Weights of collected removed particles, g
m_3	Weights of slags, g
m_4	Weights of recast layer, g
m_5	Weights of peeling substrate, g

(1987) pointed out the particle size of aluminum powders decreasing with the increase of gas pressure. Im et al. (2012) used method of aerosol flame synthesis to evaluate the size and morphology of $Gd_{0.1}Ce_{0.9}O_{2-d}$ powder. On the aspect of atomization mechanisms, Lubanska (1970) systematically studied the correlation of spray ring data for gas atomization of liquid metals with model prediction of powders. Jiang et al. (2010) reviewed physical modeling of atomization and sprays in the context of advanced computational fluid dynamics with high-order numerical schemes. On the other hand, Lin and Lin (2005) and Sweet et al. (2014) focus on characteristics and features of atomization product during heat treatment method. In the experimental study, Thompson (1948) studied the influence of the process parameters on the particle size of the atomized aluminum powder, and found that the particle size of the powder decreased with the increase of the metal flow velocity, the jet pressure and the superheat degree of the metal. Watkinson (1958) found that the use of air atomization can easily lead to oxidation of metal powder and reduce purity; inert gas atomization (nitrogen or argon) for the metal is better. Markus et al. (2002) used a high-speed photographic method to study the fragmentation of the gas stream during gas atomization, and theoretically discussed the stability of the liquid flow but did not consider the gas's compressibility. In the theoretical model study, Grant (1983) used Scheil equation to simulate the solidification behavior of atomized droplets with different parameters. Lee and Ahn (1994) modeled the effects of gas initial velocity and liquid material superheat, especially wetting angle, on the solidification behavior of individual droplets on the assumption that a droplet formed only one nucleus. Jing and Zhewei (1999) analyzed the atomization mechanism of gas atomization and summarized the process as primary crushing, secondary crushing and spherizing solidification.

It is noteworthy that almost all of the recent reports on the atomization were for metal materials. In contrast to this, the Al_2O_3 ceramic used in this work, its viscosity of molten state and step-cooling curves are different with metal. The physical properties of materials such as melting point, dynamic viscosity, surface tension, specific heat capacity, thermal conductivity, density, pyrolysis heat in the laser cutting process have a certain impact on the morphology of the molten removal. In order to explore the relationship between particle diameter of molten removal and cutting effects based on vapor-to-melt ratio, an atomization model is used to verify the theoretical and experimental analysis of the morphology of molten removal. The prediction of size of the molten droplet (removal of particles) has important guiding significance in determining the reasonable process parameters (such as the control of vapor-to-melt ratio).

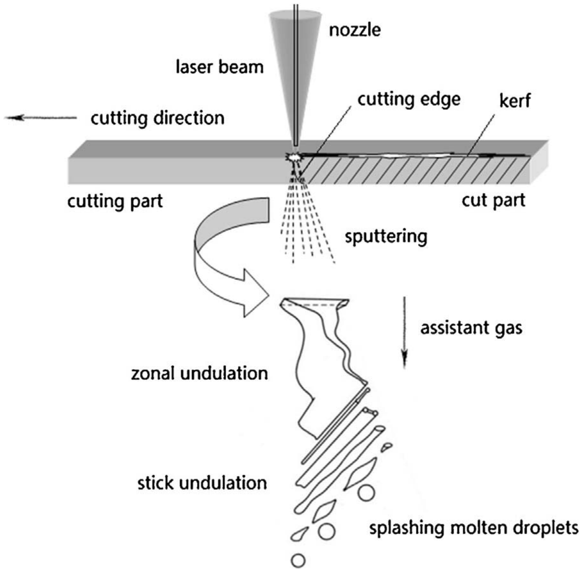

Fig. 1. Molten Removal Process of Laser Cutting Al_2O_3 Ceramic Plate.

2. Theoretical model

As shown in Fig. 1, in the auxiliary blowing effect, the molten removal process of laser cutting Al_2O_3 ceramic can be regarded as the atomization cooling process of the coaxial gas-liquid stratified jet. In this process, F Quintero et al. (2005) described the mechanism of material removal from three aspects: removal of molten material by the assistant blowing, vaporization of molten material and splashing due to recoil pressure. Luo (2016) mentioned that, material is molten into liquid with a viscosity by laser irradiation and heat absorption. The melt moves downwards under the influence of gravity and assistant pressure, and transfers heat to the underlying material for further melting. Since this energy transfer is very rapid, it can be seen as a continuous melt in the depth direction. As descriptions from Antipas (2006) and Antipas (2009), the high-speed cooling airflow from the assistant gas nozzle acts on the surface of the material melt, stretching the melt to form a certain longitudinal wave-number. The turbulence of the gas stream will fluctuate in the transverse direction of the melt band, causing the ribbon melt to break into fine droplets. These droplets are spherized under the action of surface tension and scattered into high-speed moving particles