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Morphology investigation of removal particles during laser cutting of Al_2O_3 ceramics based on vapor-to-melt ratio

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ABSTRACT

An investigation of particle morphology based on vapor-to-melt ratio is carried out to reflect the relationship between the forms of material removal and effects of cutting process. The influences of vapor-to-melt ratio on morphology of removal particles (average diameter, diameter distribution, sphericity, spheroidization rate and density distribution) is investigated by the experimental observation and analysis. It is shown that, a steady processing state with maximum average diameter, concentrated distribution, better sphericity, lager spheroidization rate and higher hollow proportion of removal particles is obtained at a relatively large value of vapor-to-melt ratio. However, at a too high value of vapor-to-melt ratio, a small quantity of material breaks and strips in a substrate form by the hot tearing effect of material. These irregular residues are mixed in the total removal collection, thereby reducing the average sphericity of the overall removal. When the particle diameter is greater than 100 μm, a complete cavity is formed close to the center, and the diameter is about 1/2 that of the whole particle.

1. Introduction

From the aspects of gas-liquid relationship, action region status and removing cooling mode, the melt removing process of alumina ceramic laser cutting can be regarded as an atomization cooling process of relatively typical coaxial gas-liquid stratified jet flows. Lawley (1977) illustrated the process that a molten material liquid flow (i.e. the molten layer) meets the high-speed airflow (argon or nitrogen) from an auxiliary gas nozzle at a certain point and is broken into fine melting droplets. Lykov et al. (2016) described that, under the action of surface tension, these melting droplet particles are spherized and rapidly cooled into alumina ceramic powder. The size, morphology and composition of particles are affected by material gasification, melting ratio and other aspects. Gunenthiram et al., 2018 obtained spherical metal particles with the diameter range of 20–100 μm, which was smaller than ceramic material of 30–180 μm. Károly and Szépvölgyi (2003) used RF thermal plasma to prepare hollow alumina microspheres and found that the morphology of molten particles reflects the effect of laser acted on the material in the processing course. The particles have some unique features such as relatively high sphericity, relatively centralized particle diameters and universal hollowness.

Scholars have conducted a series of studies on molten particles in the aspects of modeling, morphology, nature and composition. Luo et al. (2016) revealed the relationship between the processing parameters and cutting quality, which represent the influence of melting and vaporizing ratio on cutting effects. At the same time, Wang and Luo (2018) also considered that 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 in Al_2O_3 ceramics laser cutting. Thompson (1948) studied the influence of technological parameters on metal powder, and found that the powder size is reduced along with the increase of velocity of metal liquid flow, the increase of jet flow pressure and the increase of metal superheat. Zemtsova et al. (2015) synthesized micro- and nano- powders by sol-gel method to reveal the mechanical properties on particle growth rate. Gossé et al. (2006) considered two factors of particle size and morphological characterization. A hollow spherical structure is observed by SEM. Shahzad et al. (2013) expounded the cooling rate, stirring, and sintering density on polymer-ceramic composite particles. The work extended the application of alumina powder in laser sintering. Yilbas and Aleem (2006) simulated the formation of a molten layer during laser cutting of metallic material and predicted the size of particles. A high-magnification surface morphology of the spherical particle is observed through SEM.

During the laser cutting of alumina ceramics, only a small portion of removal is vaporized. In addition to recast layer, a lot of remaining material is removed as molten particles. Usually, this part of removal is discarded as waste. But the features mentioned above make these by-products can be used in the field of cold spray, laser cladding, surface

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Nomenclature

r_{vmr}	Vaporto-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 adhering slag, g
m_4	Weights of recast layer, g
m_5	Weights of peeling substrate, g
d_m	Particle diameter, μm
σ	Lognormal standard deviations, μm
n	Particle number
E	Sphericity
π	Circumference ratio
S	Area of particle section, μm^2
C	Circumference of particle section, μm^2
ρ	Density, g cm^{-3}

modification and 3D printing. Cabanillas et al. (2005) observed the removed melt particles, and pointed out the melt particles generated by laser cutting contain spherical particles, which may be used in the field of powder metallurgy. Triantou et al. (2015) used alumina cold sprayed coatings on copper and composite copper. Observation indicated that the wear rates of composite coatings containing fine Al_2O_3 particles were lower than those containing coarse Al_2O_3 particles. Leunda et al. (2016) pointed that, large crushed powders produce best results instead of small and spherical ones in laser cladding strategies for producing WC reinforced NiCr coatings inside twin barrels. Licitra et al. (2015) studied dynamic properties of alumina hollow particle filled aluminum alloy A356 matrix syntactic foams and revealed that, the lower density of filled-in hollow alumina material has lower storage modulus and loss modulus.

In reports at the present stage, for the melt removal particles generated by laser cutting of alumina ceramic, morphology or physical property analysis is seldom conducted in combination material gasification and melt removing process. By proper controlling of processing vapor-to-melt ratio, it will not only get a better cutting effect of alumina ceramics, but also to obtain ideal morphology of removal particles. In this paper, based on the morphology investigation of removal particles including particle diameters, size distribution, sphericity, spheroidization rate and density (porosity), the relationship between vapor-to-melt ratio and morphology of molten particles is discussed to further expand and extend the application range of laser processing hard-brittle ceramic material.

2. Principles and experiments

2.1. Formation of spherical particles

The diagram of the laser cutting process is shown in Fig. 1. High-energy density of laser beam irradiates on the work-piece. Melting and vaporization occur in the cutting region. A molten layer is formed between the gaseous and solid material, moving forward with the scanning beam. Part of the material under high energy density is vaporized directly, while the rest of the heat-affected zone melted. Due to assistant pressure and gravity, molten material moves downwards from the top surface. Under the cooling effect of assistant gas, the recast layer and dross are formed. More molten material leads to a thicker recast layer, higher amount of dross and removal. The control of vapor-to-melt ratio is effective and significant to improve the cutting quality of alumina sheet.

The molten removal process of Al_2O_3 ceramic laser cutting can be regarded as a typical atomization process. Material is molten into liquid with a viscosity by laser irradiation and heat absorption. Part of the melt moves downwards under the influence of gravity and assistant pressure, and finally breaks into fine droplets. Antipas (2006) and Antipas (2009) both demonstrated the formation process. These droplets are spherized under the action of surface tension and scattered into high-speed moving particles by the impact of airflow. Most of the flying droplets are rapidly cooled and solidified into Al_2O_3 ceramic particles, while a small part of droplets broken into smaller spherule. In addition, a few of tiny droplets collide and bond before solidification to form larger particles.

Pravdic and Gani (1996) reported the mechanism of particle morphology formed by the rapid cooling of molten droplets. Studies have shown that most of the condensed particles have a hollow morphology caused by the expansion of internal gas in the high temperature melting state. The applicability of this mechanism consists of the following two prerequisites. Firstly, the material composition is relatively single. So the component has a sharp flipping point, that is, the interval from softening temperature to the molten temperature is very narrow. Secondly, if the material contains a variety of ceramic components, these components must be able to form a eutectic phase during the solidification of the melt and the temperature range from the eutectic phase to the one-component flipping point cannot be large. If one of the above conditions is satisfied, it is possible to produce a molten liquid film on the surface of the particles, enclosing the internal gas, and forming molten droplets having air therein. When the droplet is finally subjected to rapid cooling, it can be quickly cooled from the outside to the inside, and the cavity structure is preserved. The Al_2O_3 content of the ceramic used in the experiment is above 96%, and the melting point is about 2310 K–2320 K without softening temperature range. The formed particles are well spherized and have a cavity structure.

2.2. Detection experiments of vapor-to-melt ratio and micro morphology

The vapor-to-melt ratio depends on the relationship between two forms of material removal, i.e., vaporization and melting. A higher vapor-to-melt ratio represents that more material is removed by vaporization, and vice versa. The r_{vmr} can be expressed as follow:

$$r_{vmr} = m_v/m_m, \tag{1}$$

where m_v is mass of vaporization (equivalent to vaporization flow rate),

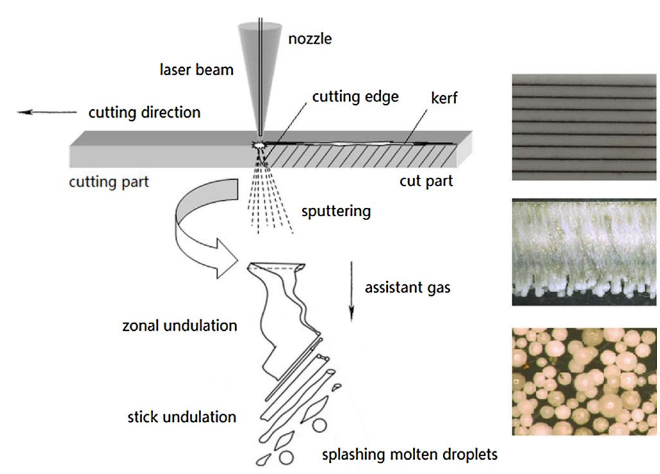

Fig. 1. Molten Removal Process of Al_2O_3 Ceramic Sheet Laser Cutting.