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Numerical simulation of single-pulse laser ablation for dressing a bronze-bond diamond grinding wheel

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ABSTRACT

To investigate the interaction between a laser beam and the bronze substrate in pulsed laser dressing of bronze-bonded diamond abrasive grinding wheels, a two-dimensional, transient numerical model of the three-phase (solid–liquid–gas) coupling in single-pulse laser ablation of the bronze was developed. The model accounts for the heat transfer, solidification, melting and vaporisation processes; the latent heat mechanism of the phase changes; and various critical factors such as surface tension, the vaporisation-induced recoil force, the thermal buoyancy force, and Darcy friction. The phase-field method is used to accurately track the development of the liquid/vapour (L/V) interface in the ablation crater. The finite element analysis software COMSOL Multiphysics was used to calculate the internal temperature field of the bronze substrate, the velocity field in the metallic vapour zone, and the evolution of the shape of the ablation crater during single-pulse laser ablation with various average laser power levels. The maximum error between the experimental results and the numerical analysis was less than 5%, which shows that the results are consistent. This model can accurately simulate the dynamic behaviour of the crater L/V interface during single-pulse laser ablation. This study provides a theoretical foundation for further research on laser dressing technology for bronze-bonded diamond grinding wheels.

1. Introduction

Laser dressing of highly abrasive grinding wheels incorporates lasers, processing of very hard materials, sensing and control, precision grinding, and computers, so this emerging technology is multidisciplinary. This technology was originally proposed by Babu [1,2] in the 1990s. This method uses pulsed-laser ablation, in which a concentrated high-energy pulsed laser beam is directed onto the surface of a grinding wheel rotating at a uniform speed. The laser beam is used as a thermal, non-contact "cutting tool", making microscopic cuts in the surface of the grinding wheel. As a result, diamond grains with sharp cutting edges are exposed. By repeating this process, the grinding wheel is dressed to provide a highly abrasive surface [3].

Over the 20 years of development of laser dressing technology, researchers have made significant progress in the selection and optimisation of the process parameters and have acquired considerable experience [4–7]. However, for this technology to be practical in industrial applications, several important problems must be addressed. These problems include rapid heating of the grinding wheel material, melting, vaporisation, heat and mass transfer, plasma shockwaves and the defocusing effect, vaporisation-induced recoil forces, and the formation of an ablation crater. A more comprehensive model of the interaction between the pulsed laser and the grinding wheel material must be developed. This model should facilitate a full understanding of the effects of the process parameters on the removal of material from the abrasive layer, the surface topography, and the surface profile after dressing. This model should also provide an important and useful theoretical basis for subsequent developments of laser dressing technology to provide high efficiency and high quality with minimal damage. However, laser dressing technology involves the interaction between a high-energy, short-pulse laser beam and a highly abrasive composite material. The model should also include the behaviour of very hard materials, incorporating multiple effects such as acoustic, thermal, mechanical, and electrical properties.

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Only a few studies have developed numerical simulations, and these have been limited to transient temperature field calculations [8–10].

This study developed a transient multiphase coupling model of single-pulse laser ablation of a bronze target with applications to the dressing of bronze-bond diamond abrasive grinding wheels. This model was developed using the COMSOL Multiphysics analysis software with the two-phase flow/phase field module included in the software. The model also includes laser vaporisation dynamics to improve the accuracy of the conventional control equation in the software module and simulates the evolution of the crater liquid/vapour (L/V) interface, the internal temperature field of the bronze, and the velocity field of the metallic vapour during single-pulse laser ablation with various average laser power levels. This study provides a systematic and fundamental theoretical framework for laser dressing technology for bronze-bond diamond grinding wheels.

2. Model development

2.1. Basic assumptions

Single-pulse laser ablation can be divided into three phases. First, a high-energy, pulsed laser beam is concentrated through an optical system and directed onto the surface of the material being processed. The rapid absorption of laser energy causes the temperature of the target to increase, and melting occurs in the target ablation area. Then, part of molten material begins to vaporise and ionise, which results in a dense, high-temperature vapour flow. This vapour generates a strong recoil pressure on the molten metal surface, which develops surface tension, that expels the metal L/V mixture, and thus an ablation crater is formed. When the laser pulse ends, the molten metal on the crater wall flows back and solidifies, forming a layer on the ablation crater surface. It is clear that pulsed laser ablation involves complex thermodynamic processes including the development of solid/liquid (S/L) and L/V interfaces and coupled heat and mass transfer. This process is extremely complex and is affected by numerous factors. To obtain an accurate model of this thermodynamic process with limited time and computing power, it was necessary to simplify the pulsed-laser ablation transient model. Therefore, the following assumptions were made:

(1) The effects on the laser beam of absorption and defocusing caused by metal particles, the vapour flow, and the laser-generated plasma over the ablation area were not considered, and the effect of the Knudsen layer on the pulsed-laser ablation process at the L/V interface was not considered;
(2) It was assumed that the laser spot was circular and the energy output followed a Gaussian distribution and was sinusoidal with time. It was further assumed that the pulsed laser beam can directly affect the thin fluid layer near the L/V interface and vary with changes in the interface;
(3) It was assumed that the bronze was uniform and isotropic and that the thermo-physical properties were independent of temperature. In addition, the liquid and gaseous states were assumed to be incompressible, ideal fluids, and the flow was assumed to be laminar.

2.2. L/V interface

The phase-field method was developed in the 1980s and is an advanced numerical method based on the Ginzburg–Landau and Cahn–Hilliard equations. The method uses a differential equation to represent the combined effects of diffusion, ordered potential, and thermodynamic driving forces. The method is particularly suitable for modelling an interface with a complex form, curvature, and motion. The algorithm is simple and powerful [11,12]. The essential principle behind this method is the use of a phase field parameter $\phi(x,t)$ (where $\boldsymbol{x}$ is a spatial variable and t is time) to represent the physical state of the system at each point in space and time. For the gaseous phase, $\phi=-1$, for the liquid phase, $\phi=1$, and in the vicinity of the L/V interface, the value of ϕ changes rapidly between -1 and 1. The solutions of the phase-field equation, the temperature field, the flow field, and other external fields are coupled to obtain an accurate representation of the pulsed-laser ablation vaporisation process.

The phase-field method can be combined with the widely used Knight vaporisation dynamics theory to derive a partial differential equation that describes the laser ablation crater L/V interface [13]:

$$\frac{\partial\phi}{\partial t}+\boldsymbol{u}\cdot\nabla\phi-\dot{m}\delta(\phi)\left(\frac{V_g}{\rho_g}+\frac{V_l}{\rho_l}\right)=\nabla\cdot\frac{\gamma\lambda}{\chi^2}\gamma\nabla\psi, \tag{1}$$

where $\boldsymbol{u}$ is the velocity vector, ∇ is the Hamilton operator, $\delta(\phi)$ is the Dirac delta function operating on the phase field variable ϕ, V_g and V_l are the volume fractions of the gaseous phase and the liquid phase, respectively, at the L/V interface at a given point (i.e., in a given grid cell in the finite element model), ρ_g and ρ_l are the densities of the material in the gaseous and liquid phases, respectively, γ is a migration adjustment variable, λ is the mixed energy density, and χ is an L/V interface layer thickness control variable. The target surface vaporisation speed $\dot{m}$ can be represented as [14–16]

$$P_{sat}(T)=p_0\exp\left(\Delta H_v\frac{T-T_v}{RTT_v}\right), \tag{2}$$

$$\dot{m}=\left(\frac{m}{2\pi k_b T}\right)^{1/2}P_{sat}(T), \tag{3}$$

where p_0 is standard atmospheric pressure ($p_0=1.013\times10^5$ Pa), ΔH_v is the vaporisation enthalpy, T is the surface temperature of the target, T_v is the vaporisation temperature, R is the universal gas constant ($R=8.314$ J/(mol K)), m is the atomic mass, k_b is the Boltzmann constant ($k_b=1.38\times10^{-23}$ J/K), and $P_{sat}(T)$ is the saturated vapour pressure of the target surface at temperature T, an expression for which can be derived from the Clausius–Clapeyron equation.

2.3. Fluid flow

If factors such as the liquid surface tension, the vaporisation recoil pressure, the thermal buoyancy, the Darcy friction, and the target surface vaporisation mass loss are taken into account, the momentum equation and the continuity equation that describe the velocity field and the pressure field over the entire computational domain can be expressed as [13]

$$\rho\frac{\partial\boldsymbol{u}}{\partial t}+\rho(\boldsymbol{u}\cdot\nabla)\boldsymbol{u}=\nabla\cdot[-p\boldsymbol{I}+\mu(\nabla\boldsymbol{u}+(\nabla\boldsymbol{u})^T)]+\boldsymbol{F}, \tag{4}$$

$$\nabla\cdot\boldsymbol{u}=\dot{m}\delta(\phi)\left(\frac{1}{\rho_g}-\frac{1}{\rho_l}\right), \tag{5}$$

where ρ is the density, p is the pressure, $\boldsymbol{I}$ is the identity matrix, μ is the dynamic viscosity, $(\bullet)^T$ denotes the transpose, and $\boldsymbol{F}$ is a generalised source term including the surface tension $\boldsymbol{F_{st}}$, the vaporisation recoil pressure $\boldsymbol{F_{rp}}$, the thermal buoyancy $\boldsymbol{F_{by}}$, and the Darcy friction $\boldsymbol{F_{Darcy}}$. The surface tension and the vaporisation recoil pressure are surface forces, and both are multiplied with the $\delta(\phi)$ function and converted into volume forces that act on the L/V interface layer in the form of a generalised source term.

The surface tension $\boldsymbol{F_{st}}$ is generated at the L/V interface by the imbalance in intermolecular forces and is expressed as [17]

$$\boldsymbol{F_{st}}=\nabla\cdot\sigma[I-(\boldsymbol{nn}^T)]\delta(\phi), \tag{6}$$

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