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Flow and heat transfer characteristics of assisting gas impingining onto an alumina coated hole in relation to laser drilling

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ABSTRACT

Flow and heat transfer characteristics of the assisting gas impinging onto the coated holes are investigated in relation to the laser drilling process. The alumina coating with thickness of 250 μm is considered at the surface of the carbon steel substrate. Three cases are considered by incorporating different locations of the coating on the carbon steel. These cases include coating at the top of the workpiece, coating at the bottom of the workpiece, and coating both at the top and at the bottom of the workpiece. A no-coating situation of the hole is also presented for the comparison reason. To resemble the laser drilling process, the wall temperature of the coating and the carbon steel substrate is kept at the melting temperatures during the simulations. A numerical scheme incorporating the control volume approach is introduced and the Reynolds stress turbulence model is used to account for the turbulence effect of the impinging assisting gas. An experiment is carried out in line with the simulation conditions to examine the morphological changes at the coating-carbon steel interface. It is found that the assisting gas temperature exceeds the melting temperature of the steel substrate along the coating thickness and as the assisting gas progresses further into the hole, heat transfer from the assisting gas to the hole wall takes place. This, in turn, increases thermal erosion at the hole wall in the vicinity of the coating-steel substrate interface. The Nusselt number and the skin friction attain large values along the coating thickness in the hole.

1. Introduction

Ceramic coatings find applications in various industries to protect the surfaces from harsh environments such as high temperature, wearing, and corrosion environments. However conventional machining of ceramic coated surfaces is difficult and requires efforts and high costs for quality processing. This is because of the high hardness and brittleness of the ceramic coatings. Laser machining of ceramic coated surfaces offers considerable advantages over the conventional methods and some of these advantages include no mechanical contact between the cutting tool and the workpiece, precision of operation, local treatment, fast processing, and low cost. During laser machining, assisting gas is used to purge the molten material from the machining sites and protects the machined surfaces from high temperature oxidation reactions such as high temperature combustions. Although assisting gas improves the machining process, it also has an adverse effect on the heating and cooling rates on the machined surfaces due to the convection heat transfer. Moreover, the melting temperatures of the coating and base material are different; heat transfer from the machined surfaces changes the thermodynamic state of the assisting gas in the hole during the processing. This, in turn, alters the Nusselt number and the skin friction on the machined surface while modifying the end product quality. Consequently, investigation into the flow and heat transfer characteristics of the assisting gas in the coated hole in relation to laser machining becomes essential.

In laser gas assisted processing, the assisting gas impinges onto the workpiece surface and modifies the heat transfer rates from the machined section. Considerable research studies were carried out to examine the jet impingement onto surfaces, which are subjected to the heating or cooling cycles, and some of these studies include the laser gas assisted processing. Twin gas jet-assisted laser drilling through thermal barrier-coated nickel alloy substrates was investigated by Sezer et al. [1]. They used the finite volume-based numerical modeling of melting flow during the drilling process incorporating the effect of the assisting gas. The influence of gas jet on nanosecond laser percussion drilling was examined by Khan et al. [2]. They introduced different gas dynamic conditions inside the holes and at the surface to correlate the drilling rates with the hole characteristics. The gas dynamic effect of the assisting gas on laser cut quality was studied by Chen et al. [3]. Their findings revealed that the deterioration of the cut quality with the gas pressure and standoff distance was

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Nomenclature

d	diffusion dissipation
D	hole diameter
H	enthalpy
h_s	heat transfer coefficient
K	thermal conductivity
k	turbulent kinetic energy
n	normal direction
p	pressure
P	rate of production
R_{ij}	Reynolds stress
Re	Reynolds no.
r	distance in the radial direction
t	time
T	temperature
u^*	friction velocity
U	arbitrary velocity
V	axial velocity component
x	distance in the axial direction

Greek

Γ	arbitrary diffusion coefficient
ε	energy dissipation
λ	turbulence intensity
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density (function of temperature and pressure for gas)
σ	variable Prandtl no.
σ_s	Stefan's constant
τ_w	shear stress
Φ	viscous dissipation
ϕ	arbitrary variable
Π	energy transport due to pressure excluding strain interactions
Π^w	energy transport due to wall reflection
Λ	energy transport by diffusion

Subscript

amb	ambient
i,j	arbitrary directions
jet	gas jet at inlet
l	laminar
max	maximum
p	a typical node in the computational grid
t	turbulent
v	viscous sub-layer
w	wall
v	viscous sublayer

closely related to the reductions in a through-kerf mass flow rate. The numerical analysis of a gas-dynamic characteristic of the assisting gas in laser machining was investigated by Guo et al. [4]. They showed that the range of parameters for machining changed slightly for different exit Mach numbers. The assisting gas effects on the laser drilling process were studied by Schneider et al. [5]. They indicated that the assisting gas limited the propagation of the vapor in the drilling section and facilitated the deposition of metallic liquid around the front surface of the holes. Laser drilling of multi-layer aerospace material systems was examined by Corcoran et al. [6]. They reported the negative effects of percussion laser drilling on material interfaces, bond strength, and the negative effects on the individual microstructures such as re-melt layers and microcracking. Spatter prevention during the laser drilling of selected aerospace materials was investigated by Low et al. [7]. They showed that due to the sufficient thermal resistance of the anti-spatter composite coating, the free space on the surfaces of the alloy substrates was eliminated and the spatter was continually ejected out of the drilling site by the high-pressure forces from the assisting gas jet and the recoil pressure.

Although thermal effects of the assisting gas on the heat transfer rates and the skin friction were investigated in the previous studies in relation to the laser drilling applications [8,10], the influence of the coating location on the heat transfer rates and the skin friction is left obscure. Therefore, in the present study, the heat transfer rates and the skin friction in the ceramic coated laser drilled holes, due to the presence of the assisting gas, are investigated. A control volume approach is introduced in the numerical simulations. To resemble the laser heating process, the hole wall temperature is assumed to be at the melting temperature of the coating and base materials. In the analysis, the Reynolds stress turbulence model is incorporated to account for the turbulence effects of the assisting gas. In order to observe the effects of the presence of coating on the surface of the hole wall, an experiment is carried out using the Nd:YAG laser. The scanning electron microscopy is used to obtain the micrographs of the morphological changes at the hole wall due to the presence of the coating.

2. Thermal analysis

The analysis presented is similar to the previous work [8–10]; however, in order to secure the completeness of analysis, the governing equations of flow including some details of the turbulence model and the boundary conditions are provided in this section.

The steady and axisymmetric flow conditions are considered and the compressibility and variable properties of the working fluid are accommodated in the analysis. The hole incorporated in the simulations consists of two-sections. The first section is alumina coating and its thickness is kept at 250 μm in the simulations and the second section is carbon steel and its thickness is 2 mm and kept constant in the simulations. The location of the coating is varied on the substrate surface. These locations include coating at the top surface of the substrate material, coating at the bottom surface of the substrate material, and coatings both at the top and at the bottom of the substrate material. In addition, a no-coating case is also provided for the comparison reason. Fig. 1 shows a schematic view of the hole geometry and the coordinate system. A constant temperature is considered at the hole wall to resemble the laser produced hole. In this case, temperature is kept at melting temperature of alumina coating (~2260 K) along its thickness and temperature is kept at the melting temperature of carbon steel (~1766 K) along the thickness of the substrate material (2 mm). Therefore, two temperature boundaries are set along the hole wall.

2.1. Flow equations

The governing flow and energy equations for the axisymmetric impinging steady jet can be written in the Cartesian tensor notation as follows:

(i) The continuity equation:

$$\frac{\partial}{\partial x_i}(\rho U_i) = 0. \tag{1}$$