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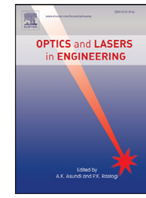

Computational and experimental study on hole evolution and delamination in laser drilling of thermal barrier coated nickel superalloy

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ABSTRACT

Computational study related to thermal stress and hole formation in laser percussion drilling of thermal barrier coated nickel alloy based on a thermal-mechanical coupled model, combined with experimental work, was conducted in this paper. The effects of laser parameters (pulse duration and laser power) and material property (elastic modulus) on delamination were discussed based on thermal stress analysis. Laser drilling with higher peak power density (>1e11W/m^2) can quickly get a through-hole of 2.3 mm within 10 pulses. Stress mutation and thermal stress shock near the interfaces are responsible for the crack formation. For the case with low peak power density, solidification rate and solidification sequence between materials should also be considered. Under the same pulse duration, the thermal stress would be enhanced with increasing of laser power. With the same pulse energy, a more intense thermal stress shock in pulse cycles can be produced under a longer pulse duration. And this shock effect near the interfaces can be alleviated when laser source is far from the interfaces. Heat accumulating effect induced by stagnation phenomenon, mainly due to lower peak power, can contribute to crack extension along the interfaces. Thus, breaking through the first two layers with high drilling efficiency is an effective way to restrain/prevent the delamination and viable parameters are also determined in the paper. Furthermore, it would offer great benefits for delamination prevention that make sure the elastic modulus of TBC and BC close to each other along the thickness with a gradually approaching method in their preparations.

1. Introduction

Laser percussion drilling is widely and massively adopted in aerospace industries for the fabrication of film cooling holes. In addition, with the development of laser technology, it has also been employed in general industrial manufacturing. For example, a periodic array of microholes on LED fabricated by femtosecond laser has also been reported for power enhancement [1]. At present, film cooling holes and thermal barrier coatings (TBC) are two main effective means to promote aircraft and gas-turbine engine efficiency and performance. The TBC system consists of a thermally insulating layer (yttria stabilized zirconia, YSZ) and an anti-oxidizing bond coat layer (MCrAlY). Padture et al. [2] have reported that such a system enabled engine to normally operate at temperatures above the melting temperature of substrate together with the cooling system. Nonetheless, the discrepancy between metals and ceramics in thermal-mechanical properties has become the greatest obstacle in laser drilling of thermal barrier coated materials involving multilayer material system. Apart from the inherent defects including spatters, microcracks as well as recast layer in laser-material interaction, the interfacial cracking (termed as delamination) would become the key issue in laser drilling of such multilayer system. Thus, a high-quality laser drilling through the TBC coated superalloy is quiet in demand. And a well and elaborative understanding of the delamination occurred at the top coat/bond coat interface (TBC/BC) as well as bond coat/substrate (BC/substrate) is of equal importance.

Apparently, laser drilling of TBC coated materials is complicated and challenging due to that it involves various materials interacting with laser and detrimental cracks can be generated at the interfaces where are not visible. Researchers are wondering what happened at the interfaces and the corresponding specific mechanisms. Thus, plenty of experimental work has been devoted to studying the delamination phenomenon. Corcoran et al. studied the effects of laser parameters and TBC density on delamination and hole microstructures [3]. It was reported that a shorter pulse width, a high density TBC and higher gas pressure can

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Nomenclature

k	thermal conductivity (W m^{-1} K^{-1})
ρ	Density (kg m^{-3})
C_P	specific heat capacity at constant pressure (J kg^{-1} K^{-1})
E	elastic modulus (Pa)
ν	Poisson's ratio
α	coefficient of thermal expansion (K^{-1})
α_A	absorptivity
Tm	melting temperature (K)
Tv	vaporization temperature (K)
Lm	latent heat of fusion (J kg^{-1})
Lv	latent heat of evaporation (J kg^{-1})
C_{pe}	equivalent specific heat capacity (J kg^{-1} K^{-1})
δ_m	normalization function around the melting temperature (K^{-1})
δ_v	normalization function around the vaporization temperature (K^{-1})
H'	smooth heaviside function
ΔT	half-width of the curve (K)
q	heat flux (W m^{-2})
n	normal vector

Subscripts

r	the radial coordinate
z	the height in z coordinate
$I(r, z)$	distribution of laser intensity
I_0	peak power intensity (W m^{-2})
v	recession rate of the vaporization front (m/s)
I	net heat flux (W m^{-2})
ω_0	waist radius
$\omega(z)$	laser spot size as a function of z
z_R	Rayleigh range
q_{inward}	inward heat flux of laser (W m^{-2})
q_{laser}	heat flux of laser source (W m^{-2})
S	area of laser spot
h	coefficient of heat convection (W K^{-1} m^{-2})
T_{amb}	ambient temperature (K)
ε	surface-to-ambient radiation
σ	Stefan–Boltzmann constant (W m^{-2} K^{-4})
ε_r, ε_θ, ε_z	strain
σ_r, σ_θ, σ_z	stress (Pa)
σ_e	the von Mises stress (Pa)
θ	the azimuth

minimize the delamination to varying degree. Voisey and Clyne carried out research on interfacial toughness of laser drilled TBCs using a spontaneous debonding technique [4]. It was found that the interfacial toughness of BC/substrate is significantly greater than that of TBC/BC and failure often occurs at the TBC/BC interface. Besides, the interfacial toughness of the TBC unexpectedly can be enhanced by laser drilling. Kamalu et al. [5] presented us a general conclusion through experimental analysis that steep temperature gradients gave rise to delamination and recoil pressure brought about the propagation of microcracking. As for this troublesome issue, further studies on delamination problem have been carried out. Sezer et al. investigated the effect of various beam angle on delamination crack size, and conclusion was drawn that crack length increases along with decreasing drilling angle [6]. Girardot et al. [7] stated that a shoulder in the hole profile can favor delamination crack propagation. Furthermore, Sezer and Li carried out a more careful and detailed study [8]. It was clearly figured out that mechanical stresses induced by melt ejection were responsible for TBC/BC delamination while thermal effect for BC/substrate delamination. With regard to TBC/BC delamination, both shear and normal forces induced by melt ejection and vapor flow, imposed on hole wall, was linked to this damage mechanism in acute angle laser drilling. Melt ejection can also result in further prorogation of already-existed microcracking. In addition, the TBC undercutting may either initiate or aggravate the TBC/BC delamination cracks. As for BC/substrate delamination, lower pulse frequency can contribute to an increased number of thermal shock cycles and subsequent formation of thermally grown oxide (TGO) at the BC/substrate interface. Another reason was the thermal stress would be enhanced due to the coefficient of thermal expansion mismatch between layers behaved significantly as a result of higher temperature near the interface. The experimental work is, assuredly, not alone in investigating the delamination mechanism. Both Sezer et al. [9,10] and Fan et al. [11] have carried out the simulation research on interfacial cracks in inclined laser drilling using computational fluid dynamics (CFD) method. The stress induced by melt ejection has attracted much attention, and Sezer et al. [9,10] pointed out that distributions of stress on the leading edge and trailing edge were quite different. Fan et al. [11] further investigated the effect of three-steps laser drilling on the melt ejection. However, both of their models are based on a predefined hole geometry, in which the laser drilling process was not taken into consideration.

In the physical models for laser drilling, Arrizubieta et al. developed a relatively simple model for evaluating the main process parameters, in which the material removal was based on the vaporization of the material [12]. Bharatish et al. evaluated the thermal residual stresses in laser drilled alumina ceramics using transient heat transfer analysis [13]. Hanon et al. investigated the effects of the laser peak power and the pulse duration on the drilling process based on the finite volume method [14]. However, all their subjects were homogenous materials, the case involving laser drilling of multilayer materials is rarely reported.

For the authors' knowledge, expect for the stress induced by molten material flow, the thermal stress generated in laser drilling process especially when laser drilling through the interfaces (TBC/BC, BC/substrate) also has a tremendous influence over the delamination, which is not carefully discussed. The thermal effect induced when melt front penetrating through these two interfaces should be at the crux of the issue. And a thermal-mechanical coupled model involving interaction of laser and multilayer material system has been also developed wherein the thermal-physical properties of various layers depending on temperatures are also taken into account. The effects of laser parameters (pulse duration and powers) and material property of three layers (elastic modulus) on such a defect were also considered. The goal of the computational study combined with experimental work reported in the present paper mainly focuses on what happened at the interfaces to explore the intrinsic mechanism of delamination from the aspect of thermal stress distribution and acquire a good knowledge of the laser drilling process through observation of hole evolution and analysis of thermal stresses.

2. Experimental methodology

2.1. Material and equipment

The laser-drilled samples employed in this study are plates of around 1.9 mm thick Inconel 718 superalloys which were atmospheric plasma sprayed with YSZ thermal barrier coating, approximately 270 μm thick and NiCrAlY bond coat with a thickness of approximately 130 µm. The laser percussion drilling process was accomplished by a fiber delivered pulsed JK 300D Nd:YAG laser (GSI, UK, $\lambda = 1064$ nm), emitting a spot size of 240 µm. The laser parameters are listed in Table 1. The focal plane has been maintained constant for all the tests and laser beam has a vertical incidence to the material surface. The experimental setup of laser drilling system is depicted in Fig. 1.

2.2. Process parameters and material characterization

2.2.1. Process parameters

In the study, various pulse durations (0.2 ms, 0.5 ms and 1 ms) with different pulse energies were employed for this investigation. For the