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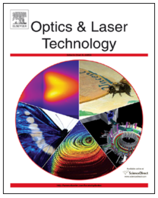

Laser cutting of rectangular geometry in 2024 aluminum alloy: Thermal stress analysis

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ABSTRACT

Laser cutting of rectangular geometry in 2024 aluminum sheet is carried out under high pressure nitrogen assisting gas. Temperature and thermal stress fields are predicted in the cutting region incorporating ABAQUS finite element code. Morphological and elemental changes in the cutting section are analyzed using optical and scanning electron microscopes, and energy dispersive spectroscopy. Surface temperature rise in the vicinity of the cut edges is measured incorporating the thermocouples and the findings are compared with their counterparts obtained from the simulations for the validation purposes. It is found that temperature predictions agree well with the thermocouple data. von Mises stress attains significantly high values in the close region of the corners of the cut edges and mid-thickness of the cutting section along the rectangular geometry. The laser cutting section is free from large asperities such as cracks and sideways burnings; however, local dross attachment is observed at the kerf exit.

1. Introduction

Aluminum 2024 alloy is widely used in aerospace industry because of its high strength to weight ratio and good fatigue resistance [1]. Copper is the primary alloying element and the alloy surface is often clad with Al–Zn for corrosion protection despite the coating lowers the fatigue strength [2]. Conventional machining of the aluminum alloy is possible; however, the machining may not be cost effective when the high precision is required. Laser machining of the alloy offers considerable advantages over the conventional machining processes in terms of precision of operation, short processing time, and low cost. Laser machining involves with material removal from the machining sites under the high intensity laser beam; in which case, irradiated surface reaches above the melting temperature over a small region in the substrate material, which is subjected to a machining. Since the time scale of heating is short and the rate of temperature rise is high, temperature gradient developed in the irradiated region remains high during the laser machining operation. This, in turn, results in attainment of high thermal strain and thermal stresses in the close region of the machined sections. In order to avoid the high temperature oxidation reactions and purging the molten material from the cut section during the laser cutting process, an assisting gas is used to protect the cutting section from the high temperature exothermic chemical reactions. The assisting gas also contributes to the convection cooling of the laser irradiated surface and enhances the temperature gradient in the cutting section. This further increases the thermal strain and stress levels in the cut section. However, once the maximum stress exceeds the yielding limit of the alloy, deformations and defects are formed in laser irradiated region, such as cracks in the cut section while limiting the practical applications of the end product. Consequently, investigation of laser cutting of aluminum alloy and stress field developed during the cutting process becomes essential.

Considerable research studies have been carried out to examine laser cutting of aluminum alloys. Laser cutting of 2024 aluminum alloy was studied by Riveiro et al. [3]. They analyzed the microstructural characterization, grain morphology, kerf dimensions, and surface finish of the cuts and indicated that the cut edges were free from dross and cracks and the heat affected zone was negligible small. Microstructural study of laser machined 2024 aluminum alloy was presented by Araujo et al. [4]. They showed that α-liquid phases were present in the heat affected zone during the machining process and the use of the high pressure N_2 gas resulted in various types of roughness at the kerf surface. Mechanical behavior of laser machined 2024 aluminum alloy was investigated by Carpio et al. [5]. They demonstrated that the fatigue behavior of the laser treated workpiece was significantly improved

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Nomenclature

a	Gaussian parameter
$\mathbf{b}$	body force density
Cp	specific heat
d_o	stress free spacing
d	spacing measured at each tilt angle
$\underline{\underline{\mathbf{D}}}$	forth order isotropic elasticity tensor
E	Young's modulus
H	temperature dependent enthalpy including the latent heat of solidification
h_f	forced convection heat transfer coefficient due to the assisting gas
h	heat transfer coefficient due to natural convection
I_L	laser power intensity at the workpiece thickness
I_o	laser power peak density
$\underline{\underline{\mathbf{I}}}$	fourth order identity tensors
$\mathbf{I}$	second order identity tensors
k	temperature dependent thermal conductivity
K_B	bulk modulus
r_f	surface reflectivity
S_o	heat source term resembling the laser beam
t_h	workpiece thickness
T_s	surface temperature
T_{amb}	ambient temperatures
U	internal energy
u	displacement
x	axis
y	axis
z	axis

Greek Symbols

α_T	coefficient of thermal expansion
δ	absorption coefficient
δ_{ij}	Kronecker's delta
ε	emissivity (ε=0.9 is considered)
$\dot{\varepsilon}_{el}$	elastic strain rate tensor
$\dot{\varepsilon}_{ie}$	inelastic (plastic+creep) strain rate tensor
$\dot{\varepsilon}_{th}$	thermal strain rate tensor
$\bar{\varepsilon}_{el}$	equivalent inelastic strain
$\dot{\bar{\varepsilon}}_{el}$	equivalent inelastic strain-rate
ν	Poisson's ratio
ρ	density
ψ	tilt angle
σ	Stefan–Boltzmann constant
$\boldsymbol{\sigma}$	nominal stress tensor
$\dot{\sigma}$	stress rate
μ	shear modulus
$\otimes$	notation for outer tensor product
σ'	deviatoric stress tensor

due to the surface roughness resulted by a surface melting during the laser processing. Laser cutting of aluminum alloy sheet was studied by Wang et al. [6]. They showed that the particles ejected from the cut section were in a spherical form for high values of the vapor–melt ratio and the average diameter of the particles became small for the improved quality of cutting. Investigation of laser cutting of aluminum alloy and quality assessment of cut sections were carried out by Stournaras et al. [7]. They introduced a statistical analysis to assess the effect of each parameter on the cutting quality and performed the regression analysis for the development of empirical models, which could describe the effect of process parameters on the quality of laser cutting. Thermal stress fracture mode of laser cutting of aluminum nitride was examined by Molian et al. [8]. They demonstrated that the thermal stress method adopted in the study offered significant benefits such as improved precision and better cut quality. Laser cutting of aluminum nitride was examined by Migliore and Ozkan [9]. They indicated that the high thermal conductivity that made aluminum nitride useful; however, nitriding made it difficult to machine with a laser because of the material, which could absorb considerable incident energy without melting or vaporizing. Laser cutting of AlSi-alloy/SiCp composite was studied by Grabowski et al. [10]. They demonstrated that increasing laser beam scanning speed increased the slope of cutting front. Fusion cutting of aluminum, magnesium, and titanium alloys using high-power fiber laser was carried out by Scintilla and Tricarico [11]. They demonstrated that good cut quality and high productivity could be possible for light alloys using the high-power fiber laser. Laser hole cutting in aluminum foam and the influence of hole diameter on thermal stress were studied by Yilbas et al. [12]. Their findings revealed that defect free cutting of small diameter holes was possible in 8 mm thick aluminum foam and air trapped in the pores prior to laser cutting underwent oxidation reactions with molten material while forming Al_2O_3 and AlO compounds at the cut surfaces. The optimization study due to the quality assessment of laser cut straight profiles in thin Al-alloy sheet was presented by Sharma and Yadava [13]. They introduced the entropy method to determine the weight corresponding to each quality characteristic. The modeling and optimization study for the kerf taper due to a pulsed laser cutting of duralumin sheet were carried out by Pandey and Dubey [14]. They proposed the empirical model for kerf/taper variation during the laser cutting process. Thermal stress distributions and microstructure in laser cutting of thin aluminum–silicon alloy sheet were investigated by Akhtar et al. [15]. They indicated that the high conductivity of aluminum–silicon alloy increased the cooling rates and influenced the thermal stress field in the cutting section.

Laser cutting of aluminum alloys was investigated previously [16,17]; however, laser cutting of 2024 aluminum alloy and thermal stress distribution in the cut section are not explored. Therefore, in the present study, laser cutting of a rectangular geometry into 2024 aluminum alloy is carried out. Thermal and stress fields developed around the cut edges are predicted numerically using ABAQUS finite element code [18]. Temperature rise in the vicinity of the cut section is measured and compared to that obtained from the simulations. The features of the cut section and morphological changes are examined at the kerf surface using the scanning electron microscope.

2. Heating and thermal stress analysis

In the heating analysis, temperature-dependent properties, latent heat effects because of phase change, and elasto-plastic behavior of the substrate material are incorporated. Since the thermal analysis is given in the early studies [19–21], it is presented briskly below for the completeness of the arguments. The schematic view of the laser cutting of rectangular geometry and the coordinate system is shown in Fig. 1. The heat equation pertinent to the laser heating process can be written as:

$$\rho\frac{\partial(H(T))}{\partial t} = (\nabla(k(T)\nabla T)) + \rho U\frac{\partial(Cp(T)T)}{\partial x} + S_o \qquad (1)$$