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Laser treatment of dual matrix cast iron with presence of WC particles at the surface: Influence of self-annealing on stress fields

B.S. Yilbas [a,*], S.S. Akhtar [a], C. Karatas [b], K. Boran [c]

[a] Mechanical Engineering Department, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia
[b] Engineering Faculty, Hacettepe Universitesi, Ankara, Turkey
[c] Faculty of Technology, Gazi Universitesi, Ankara, Turkey

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ABSTRACT

Laser control melting of dual matrix cast iron surface is carried out. A carbon film containing 15% WC particles is formed at the surface prior to the laser treatment and the spiral tracks are adopted for laser scanning at the workpiece surface. Morphological, metallurgical, microhardness, and scratch resistance of the laser treated surface are examined using analytical tools. Temperature and stress fields in the laser irradiated region are predicted incorporating ABAQUS finite element code. Predictions of temperature and residual stress at the laser treated surface are validated with the thermocouple and the X-ray diffraction data. It is found that surface temperature and residual stress predictions agree well with their counterparts corresponding to thermocouple data and findings of X-ray diffraction technique. Laser treated surface is free from asperities including voids and micro-cracks despite the mismatch of thermal expansion coefficients of WC and dual matrix cast iron. This behavior is attributed to the self-annealing effects of recently formed spiral tracks on the previously formed tracks during the laser treatment process; in which case, the self-annealing effect modifies the cooling rates and lowers thermal stress levels in the laser treated layer. Laser treated layer consists of a dense region composing of fine grains and WC particles, dendritic and featherlike structures below the dense layer, and the heat affected zone.

1. Introduction

Laser treatment of metallic surfaces improves tribological and mechanical characteristics of the surfaces [1] and extends the fatigue life [2]. In addition, laser processing has several advantages over the conventional methods because of the local treatment, precision of operation, and the low cost. In laser surface processing, many factors affect the end product quality assessed by surface texture, microhardness, scratch resistance, microstructure, morphology, and etc. The selection of the process parameters plays a major role in achieving the desired end product quality of the laser treated surface. Since laser treatment involves with high temperature processing, rapid solidification under high cooling rates results in high thermal stress levels in the laser treated region. This, in turn, causes asperities such as voids and micro-crack networks in the treated region and limits the practical applications of the laser treated surfaces. Laser control melting improves the surface quality; however, the residual stress formed at the surface region lowers the fracture toughness and the performance of the surface response to the tribological tests [3]. The self-annealing affect created during laser treatment is one of the solutions to minimize the high stress field formed in the laser treated layer. In this case, heat conduction across the path of laser scanning and laser repetition rate during the surface processing may create a self-annealing affect in the treated layer. Moreover, the laser treatment of metallic surfaces with presence of hard particles, such as WC, require proper control and appropriate selection of the laser treatment parameters due to the mismatch of thermo-mechanical properties of the constituting elements in the treated layer. On the other hand, the model studies provide useful information about the physical processes, in terms of thermal and stress fields, taking place during the laser treatment process. Consequently, investigation of the laser treatment of metallic surfaces with presence of hard particles and thermal stress field developed in the treated layer becomes essential.

Considerable research studies were carried out to examine laser treatment of steel and iron based composites. Laser treatment of dual matrix structured cast iron surface was investigated by Sun et al. [4]. They showed that the wear resistance of the treated layer was almost 1.6 times of that of the nodular cast iron substrate. The improvement in wear resistance was due to combined results of

* Corresponding author.
E-mail address: bsyilbas@kfupm.edu.sa (B.S. Yilbas).

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Nomenclature

a	Gaussian parameter
b	body force density
Cp	specific heat
d_o	lattice stress free spacing
d	lattice spacing measured at each tilt angle
$\underline{\underline{D}}$	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_o	laser power peak density
$\underline{\underline{\mathbf{I}}}$	fourth order identity tensors
I	second order identity tensors
k	temperature dependent thermal conductivity
K_B	bulk modulus
p	geometric parameter for spiral motion
q	geometric parameter for spiral motion
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_s	scanning speed
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
θ	rotational angle
ψ	tilt angle
σ	Stefan–Boltzmann constant
σ	nominal stress tensor
$\boldsymbol{\sigma}_s$	Stefan–Boltzmann constant
$\dot{\sigma}$	stress rate
μ	shear modulus
$\otimes$	notation for outer tensor product
σ'	deviatoric stress tensor

the grain refining effect, the solution strengthening effect, the distribution of the hard phases, the work hardening effect of the retained austenite, and the good bonding between these hard phases and the Fe-based matrix. Laser alloying of cast iron and nano-mechanical properties were examined by Yang et al. [5]. They demonstrated that the resistances of plastic deformation and oxidation reaction in alloying zones were main reasons for inhibiting cracking. The alloying zone could also be considered as enlarged hard phase because of the high nano-hardness, which contributed to cracks blocking. Laser surface melting of nodular cast iron was studied by Benyounis et al. [6]. They indicated that the laser-melted zone exhibited finer dendrites of retained austenite surrounded by a continuous network of Fe_3C; in addition, some needles of martensite within the dendrites were also observed. Investigation of the wear characteristics of laser surface treated cast iron cylinder was carried out by Duffet et al. [7]. They showed that high density of lamellae structure was formed in the laser treated layer, which improved the tribological properties of the surface. The influence of laser surface texturing on the frictional behavior of cast iron was studied by Kim et al. [8]. They demonstrated that the aspect ratio of the dimples formed during the laser treatment was found to be the most significant factor influencing the friction coefficient; however, the effect of the surface density of the dimples on the coefficient of friction was only marginal. The friction and wear behavior of nodular cast iron modified by a laser micro-precision treatment were investigated by Xia et al. [9]. Their findings revealed that the substantial increase in the wear-resistance of the cast iron was observed after the laser treatment process. This could be attributed to a significant increase in the surface hardness of the laser-modified layers. Laser surface hardening of austempered ductile iron grades was examined by Soriano et al. [10]. They showed that a coarse martensite with retained austenite structure was found in the treated area, which resulted in a wear resistant and high hardness effective layer of 0.6–1 mm thickness. Laser cladding of Co-based alloy on cast iron was carried out by Ocelík et al. [11]. They developed the relationships between the laser cladding parameters (i.e. laser beam scanning speed, laser output power, and powder feeding rate) and the geometrical characteristics of a single laser track (height, width, and dilution). Surface morphology of stainless steel irradiated by a nanosecond Nd:YAG pulsed laser was studied by Liu et al. [12]. They indicated that irradiation due to several consecutive pulses caused significant damage and enhanced the stainless steel surface roughness. The characteristics of treated zone processed by pulsed Nd-YAG laser surface remelting on hot work steel were investigated by Zhang et al. [13]. They showed that that different combinations of average peak power density and effective peak power density could vary the appearance of cross-sectional morphology, microstructure and hardness. Investigation of the different surface morphologies formed on AISI 304 stainless steel via millisecond Nd:YAG pulsed laser was carried out by Cui et al. [14]. They demonstrated that the smooth surface was not obtained under over-high laser energy densities; in addition, the schematic relationship was used to describe the formation process and mechanism of different surface morphologies. Surface properties of low alloy steel treated by plasma nitrocarburizing prior to laser quenching process were investigated by Wang et al. [15]. They indicated that the laser quenched layer exhibited enhanced wear resistance, due to the lubrication effect and optimized impact toughness, which was contributed to the formation of oxide film consisting of low nitrogen compound and iron oxidation. Laser surface modification of thermally-sprayed Diamalloy 2002 coating was carried out by Gisario et al. [16]. They indicated that laser treatment modified the surface morphology and the surface textures with low roughness. Laser surface treatment of aluminum based composite mixed with B_4C particles was examined by Yilbas et al. [17]. They demonstrated that fine grains and ultra-short dendrites were formed in the surface region of the