Optics & Laser Technology 52 (2013) 21–29

Contents lists available at SciVerse ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Predicting residual and flow stresses from surface topography created by laser cutting technology

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ARTICLE INFO

Article history:
Received 13 November 2012
Received in revised form
27 March 2013
Accepted 29 March 2013

Keywords:
Residual stress
Surface topography
Laser cutting

ABSTRACT

The paper deals with the engineering method for laser cutting technology that utilizes stress equations derived from surface topography for determining residual stresses. It presents an original method for residual stress assessment in a non-contact and non-destructive manner. The high temperature around cut edges results in the development of residual stresses during the cutting process, which decreases the quality of the end product. Surface topographical parameters themselves carry information on a concrete state of technological process in the concrete moment of its usage. This method for the assessment of residual stress in materials being cut by a laser beam provides sufficient information on the residual stress state evaluation with sufficient accuracy by applying an analytical and experimental approach. Experiments were conducted on three different materials, namely steel, aluminium alloy and titanium. It was necessary to check calculation by measuring the residual stress distribution in the vicinity of cut edge using the ultrasonic method. The novelty of the method for the determination of residual stresses in a workpiece lies in the physics-based approach focusing on the mechanical and stress-deformation parameters of the material being cut and on the mechanical equilibrium of the system: material properties—tool properties—deformation properties.

1. Introduction

The utilisation of laser cutting as one of means to optimise steel designs in manufacturing industries has increased rapidly during the last few decades. Laser cutting provides tighter tolerances and better quality cuts that reduce the need for secondary clean-up at their end. Laser cutting is mainly a thermo-mechanical process. The principle of this type of material cutting consists in focusing the laser beam on a workpiece; the material heats up so much that it melts or evaporates [1]. Deformation and also structural changes occur as a result of generated high temperatures and the cut material will appear to be striated [2].

Surface integrity is associated with the manufacturing process and covers three aspects: surface roughness, microstructure transformations and residual stress. The size and the development of flow and residual stresses after laser cutting depend on several factors. One of the most important factors are stress-deformation and thermo-elastic properties of materials, such as Young's modulus E_{mat}, yield strength $R_{p0.2}$, ultimate tensile strength R_m, elongation at failure A, specific heat C and material density γ. The prediction of residual stresses is not an easy task owing to the complexity of laser cutting process. In material laser processing, such as laser cutting, the target material is inevitably subjected to intensive non-uniform temperature changes, and as a consequence, a complex residual stress distribution is formed near the processed area. An unfavourable stress distribution may result in microcrack formation and propagation, reduction in the fatigue life of a part, and lead to catastrophic failures. According to the present state, the application of methods for residual stress assessment after laser cutting is limited to special problems and to the determination of the field variable and conditions of the physical process and convert them into mathematical terms. A reliable result on the stress values and on the stress state is possible if material surface structure is well known. Some aspects of the physical process involved in laser cutting process are difficult or impossible to study through experimental techniques, such as residual stress distribution. The generated residual stresses

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http://dx.doi.org/10.1016/j.optlastec.2013.03.024

Nomenclature

A	elongation [%]
d_0	inner diameter of the hole [mm]
d_i	spacing measured at each tilt angle [mm]
d_n	outer diameter of the hole [mm]
E	Young's modulus [GPa]
E_{mat}	material's elastic modulus [GPa]
E_{ret}	decomposition of E_{mat} for tension [MPa]
E_{retz}	decomposition of E_{mat} for pressure [MPa]
h_o	depth of cut [mm]
h_{cut}	depth level of neutral plane [mm]
h_{elm}	depth at the level of the elastic limit [mm]
h_{iz}	depth of initial zone [mm]
h_j	unit depth of cut (mm)
h_{lim}	limit depth of cut
h_{max}	depth at the level of reaching $\delta_{max}=90^\circ$ [mm]
h_{rm}	depth at the level of the ultimate strength R_m [mm]
h_{rel}	relative depth [-]
h_{rem}	depth at the level of the yield point [mm]
h_{ptm}	depth at the level of the engineering strength [mm]
h_x	general level [mm]
$h_{\delta max}$	depth at the point of δ_{max} [mm]
K_{cut}	mechanical parameter of cuttability of materials [μm]
K_{cutL}	constant of cuttability of the material for laser [μm]
K_{Iprz}	coefficient of intensity for the tensile component of the stress [MPa]
K_{IPret}	coefficient of intensity for the compressive component of the stress [MPa]
K_{pl}	coefficient of surface plasticity [μm mm]
p	gas pressure [MPa]
Ra	arithmetic average deviation of the assessed profile [μm]
Ra_o	roughness at the neutral plane [μm]
Ra_d	actual topographical function [μm]
Ra_{rad}	subsidiary topographical function in the radial direction [μm]
Re	elastic limit [MPa]
Rm	breaking strength [MPa]
$R_{p0.2}$	yield strength [MPa]
Rz	average maximum height of the profile [μm]
Rz_T	topographical function [μm]
Rz_0	surface roughness at the neutral plane [μm]
ν	Poisson's ratio [-]
V_{dj}	unit volume of deformation [m^3]
v_p	traverse speed [mm min^{-1}]
v_{Lm}	static value of longitudinal ultrasonic velocity [m s^{-1}]
v_{Ltotal}	total longitudinal ultrasonic velocity [m s^{-1}]
Y_{ret}	retardation of the trace [mm]
Y_{retj}	unit retardation of the trace [mm]
Y_{ret0}	retardation at the neutral plane [mm]
W_{las}	laser power [W]
Δv_L	change of longitudinal ultrasonic velocity [m s^{-1}]
Δvp_{total}	total change of longitudinal ultrasonic velocity [m s^{-1}]
β	acoustoelastic constant [m s^{-1} MPa^{-1}]
β_{maxAl}	acoustoelastic constant for aluminium [m s^{-1} MPa^{-1}]
β_{mazSt}	acoustoelastic constant for steel [m s^{-1} MPa^{-1}]
β_{maxTi}	acoustoelastic constant for titanium [m s^{-1} MPa^{-1}]
δ	deviation angle of trace [°]
δ_0	deviation angle of trace at the neutral plane [°]
σ_{def}	flow stresses [MPa]
σ_d	compressive stress [MPa]
σ_t	tensile stress [MPa]
σ_{dtrue}	true flow stress [MPa]
σ_{res}	residual stress [MPa]
σ_{resRa}	residual stress from surface topography [MPa]
σ_{res0}	residual stress at the neutral plane [MPa]
σ_{resM}	residual stress obtained from measurement [MPa]
σ_{resY}	residual stress according to Yilbas [MPa]
σ_{ret}	tensile component of the flow stress [MPa]
σ_{retel}	modular component for determining the elasticity limit [MPa]
σ_{retre}	modular component for determining the yield stress [MPa]
σ_{rz}	compressive component of the flow stress [MPa]
σ_{rz0}	compressive component of the flow stress at the neutral plane [MPa]
σ_{rzx}	attenuation component of σ_{rz} [MPa]
σ_{res0}	residual stress at the neutral plane [MPa]
σ_{resx}	residual stress at the general level [MPa]
σ_{sum}	quadratic sum of the tensile and compression component [MPa]
ψ	tilt angle [°]

can be taken as a criterion for the similarity with other technologies. It is generally known that the absolute value of the residual stress close to the surface of the workpiece is high and decreases with an increase in the depth. It is valid for common technologies, such as chip machining, turning, etc. The rigid tool does not swerve and with an increase in the depth of cut, a volume of material removed also increases and the generated residual stresses are lost [3–5]. The mechanism of laser cutting as a mechanically flexible tool with thermal effects and many other factors participating in the mechanism of material disintegration is, from the point of view of analytical approximation, elaboration and description, very problematic. The cutting resistance of material is represented by the behaviours of deformation functions of disintegration tool of stiff type and that of flexible-type of laser beam, respectively. In machining practice applying the technologies that use flexible types of tools, such as abrasive waterjet, laser, plasma, the curvature of traces of cuts is a big problem. The instability of the direction of penetration of flexible-type tools through the material generates a relatively high waviness and roughness on machined surfaces. There is little data available about residual stresses developed during laser cutting. Significant research findings in the field of laser cutting and residual stress evaluation has been made by Yilbas et al. [6–9]. He investigated residual stress after laser cutting of holes in a mild steel thick sheet. The thermal and stress fields developed during the cutting process predicted through the finite element method. The material is being modelled as thermo-elasto-plastic with temperature dependent material properties, where plasticity is modelled by using the von Mises criterion. He also developed a computerized method of modelling residual stresses during laser cutting, which was accepted as a patent in 2010. Zamachtchikov et al [10] developed a method to evaluate residual stresses in the laser cutting process. He utilised the direct relationship between residual stresses and strains. However, the method described is interesting in those cases where an approximate and rapid but not detailed evaluation of the residual stresses is required. In fact, only a few researchers are involved in this area of research. There is little data available about residual stresses developed during laser cutting. Residual stress generation due to laser cutting has not been studied so much as after laser welding [11–13]. It should be