ELSEVIER

Optics & Laser Technology 33 (2001) 7–13

Optics & Laser Technology

www.elsevier.com/locate/optlastec

A melt depth prediction model for quality control of laser surface glazing of inhomogeneous materials

A.A. Peligrad[a,*], E. Zhou[a], D. Morton[a], L. Li[b]

[a] Faculty of Technology, Bolton Institute, Deane Road, Bolton BL3 5AB, UK
[b] Manufacturing Division, Department of Mechanical Engineering, UMIST, Sackville Street, Manchester M60 1QD, UK

Received 8 June 2000; received in revised form 29 August 2000; accepted 4 September 2000

Abstract

This paper reports on an investigation into the development of an analytical model for the quality control of laser marking/engraving of clay tiles using a high-power diode laser (HPDL). An analytical model for the laser melting of inhomogeneous workpieces with parabolic melt pool geometry being assumed was developed. The theoretical results were compared with the experimental data. The predicted melt pool depth and the experimental values were in close correlation with the parameter $P_L/\sqrt{dv}$ for values less than $15\,\mathrm{W\,mm^{-1}\,s^{-1/2}}$, in spite of simplifications introduced in the model. At the relatively large values of parameter $P_L/\sqrt{dv}$ the assumption of parabolic melt pool shape and one-dimensional heat transfer no longer holds true.

Keywords: HPDL; Analytical model; Quality control; Tiles glazing

1. Introduction

The development of an accurate analysis procedure for laser applications, including marking/glazing of building materials, is extremely complicated due to many process parameters involved. Variations in the quality of the marking process may be observed between processing cycles performed with the same laser equipment, and apparently constant operating conditions and material properties. This poor reproducibility arises from the high sensitivity of the laser marking process to small changes in the operating parameters (such as laser power and beam velocity stability), as well as to process disturbances (such as varying absorptivity, surface texture changes, geometry changes and workpiece thickness changes). Therefore, monitoring and control of the laser marking parameters are necessary. The parameters that can be measured on-line include melt pool surface temperature and melt pool surface area. The development of a suitable model to predict these parameters can provide knowledge of process performance as well as the prediction of the marking process. This paper presents an analytical model for the melt pool depth geometry in case of high-power diode lasers (HPDL) engraving of clay tiles.

High-power diode lasers (HPDL) are emerging as an alternative to "traditional" laser systems in applications other than the medical field. With the availability of fibre-delivered laser systems up to 120 W-cw output power, with focused spot sizes down to 200 μm diameter and for stacked systems of up to 3 kW cw with a $1 \times 3\,\mathrm{mm}^2$ beam spot, they are fast becoming an alternative method for material processing [1–3].

Li et al. [4] studied the basic mechanisms and the characteristics of the beam absorption in case of laser marking/engraving building materials such as: marble, bricks, granite, ceramic tiles, etc. This work considered the effects of glazing mechanisms, material texture, colour, laser process parameters and atmospheric conditions on the marking process. The present paper looks into the optimal operational parameters that will help design a model for controlling the quality of the laser marking/glazing process.

Lawrence [5] has developed an analytical model capable of modelling the ceramic tile grout sealing process. He has considered an ABAQUS FEM model for temperature prediction and compared it with the temperature profile, predicted by Carslaw and Jaeger [6]. This actual paper seeks to develop a model for laser glazing clay tiles based on the variation of the melt pool geometry rather than temperature.

* Corresponding author. Tel.: +44-01204-903107; fax: +44-01204-381107.

E-mail address: aap1res@bolton.ac.uk (A.A. Peligrad).

0030-3992/01/$ - see front matter
PII: S0030-3992(00)00107-9

It has been demonstrated that the relative increase of the melt pool area, due to an increase in laser power, is much larger than the relative increase of the melt pool temperature [7]. This result supports this idea that the melt pool area is the right parameter for the feedback control.

Understanding the physical phenomena that occur during laser marking/glazing is relevant for modelling the process. The models resulting from the conservative of energy (heat conduction energy) are used to analyse the effects of the laser power and beam traverse velocity on the temperature distribution and melt pool dimensions. The results from this analysis would be used for the design of a closed-loop control system.

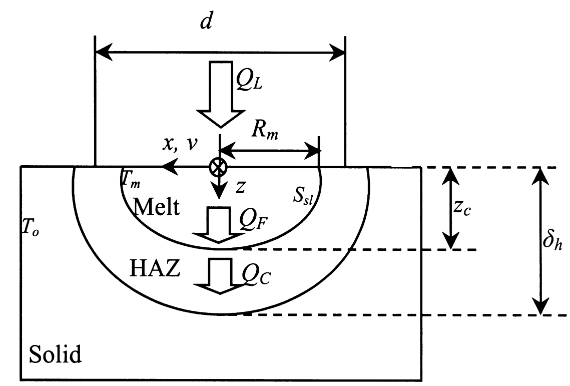

Fig. 1. Melt pool geometry and energy flows in a quasi-stationary situation.

2. Physical phenomena which occur during laser marking/glazing

In the case of laser marking/glazing clay tiles melting dominates the process. The temperature distribution in a semi-infinite workpiece during laser marking can be described by the heat conduction equation [6].

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (K \nabla T) + \nabla \cdot (\mathbf{U} \rho c_p T) = Q, \tag{1}$$

where T (K) denotes the temperature at (x, y, z, t) relative to the ambient temperature T_0 (K), t (s) denotes time, ρ ($\mathrm{kg\,m^{-3}}$) is the density of the material, c_p ($\mathrm{J\,kg^{-1}\,K^{-1}}$) is thermal capacity, and K ($\mathrm{W\,m^{-1}\,K^{-1}}$) is thermal conductivity. $\mathbf{U}$ denotes the fluid flow velocity with respect to the coordinate system (x, y, z) fixed to the laser beam, and Q ($\mathrm{W\,m^{-3}}$) represents the heat source and heat sinks in the work piece.

There are three types of heat transfers involved in clay marking with a laser: radiation, conduction and convection heat transfer [8]. When the laser beam impinges on the surface of an opaque workpiece, a portion of this radiant energy may be reflected back to the environment, transmitted into the workpiece interior, or absorbed by the surface. This interaction represents *radiation* heat transfer [9]. The fraction of the total beam energy absorbed by the workpiece depends on the optical properties of the material.

The absorbed beam energy is transformed into thermal energy through lattice vibrations in the material at the beam/material interaction zone. An increase in lattice vibration results in an increase in the temperature at that location.

When the local temperature reaches the melting temperature, phase changes may occur. Some of the absorbed energy may be transferred to atoms in the workpiece interior through lattice vibration; this effect is called *conduction* heat transfer [10]. The presence of conduction dissipates thermal energy, which would otherwise be used to melt or vaporise additional material. Thermal energy may also be dissipated from the beam/material interaction zone to the environment under the influence of fluid flow; this interaction is called *convection* heat transfer. Convection heat transfer is influenced by the fluid mechanics of the gas flow near the melt pool and the traverse speed. A well-known approach to solve the heat conduction equation (1), given its boundary and initial condition, is by the use of Green's functions [6].

3. Melt pool geometry calculation

The melt pool depth during laser marking determines the thickness of the resulting surface layer after solidification (i.e. the glaze thickness), which is related to the quality of the mark. Therefore, it is important to know the relationship between the geometrical dimensions of the melt pool and the operating parameters, such as laser power and traverse speed. A simple analytical model can be derived by considering the heat flow down the centreline of the melt pool as approximately one dimensional. This assumption implies that the melt pool is extensive and flat, though in practice it is nearly parabolic (see Fig. 1). Similar assumptions have been considered by Römer [7], for laser surface treatment of titanium nitride.

The energy balance within the sample consists of three terms: the absorbed laser energy Q_L, the energy Q_C transported by heat conduction from the liquid–solid interface of the melt pool into the non-molten material, and the energy Q_F required to create a melt pool. Due to the relative velocity between the laser beam and the workpiece, energy is quickly removed from the interaction zone (convective losses). The energy Q_F required to create a melt pool is accounted for in the energy balance to compensate for these convective losses. In the case of marking/glazing building materials, no gas flow is required for the process, apart from a low flow rate coaxial gas ($3\,\mathrm{l\,min^{-1}}$) (in order to protect the optics). This flow would cause negligible convection loss. Then the heat balance equation is

$$Q_\mathrm{L} = Q_\mathrm{C} + Q_\mathrm{F}. \tag{2}$$