A simple method for the estimation of laser absorptivity using heat sensitive paints

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Abstract. The emergence of high-power diode laser technology has paved the way for the widespread integration of laser processing into metal cutting machine tools. Such integration is of significant benefit not just in terms of better logistics and work flow, but also enhanced process capability and flexibility, and part quality. This is particularly true in the batch manufacture of high-value components, wherein it is essential to employ mathematical models to formulate and optimize operating parameters. Consequently, there is an industrial need for a simple and inexpensive technique for the rapid estimation of the laser absorptivity of a surface, which is of critical influence in the effective practical application of process models. To this end, this design note proposes a method that involves an analytical model and a novel experimental technique based on temperature indicating paints, for estimating the absorptivity of a surface.

Keywords: absorptivity, high-power diode laser, temperature indicating lacquer.

1. Introduction

A topic of significant current research interest is the integration of diverse manufacturing processes. The most common amongst such appears to be the incorporation of high-power lasers into metal cutting machine tools. The rationale for such integration are manyfold. In laser-assisted machining, a laser heats the workpiece material in the vicinity of the shear zone to improve its machinability. Laser surface hardening in a machine tool presents advantages such as the capability for selective heat treatment, in addition to better logistics and material flow that in themselves represent a notable improvement in production efficiency; localized surface hardening can also be employed to reduce the incidence of machining-induced burrs. Laser technologies such as alloying that entail surface melting necessitate the surface to be finish machined, which further renders it beneficial to incorporate a laser into a machining center.

Applications that involve a laser integrated into a machine tool typically refer to batch production of critical, high-value components that does not allow for expensive prototype try-outs. It is hence essential to appropriately formulate and optimize the operating parameters prior to actual manufacture, for which mathematical process models are used [1, 2]. A critical parameter in the successful implementation of such models is the absorptivity (coupling rate) of the surface, which is the fraction of the incident laser power absorbed by it. Small changes in absorptivity can correspond to significant differences in the process response. Absorptivity is further influenced by several factors such as the material, local temperature, laser wavelength, and the characteristics of the surface such as its roughness, and the presence of any oxides or coatings. Experimental techniques for reliably estimating the absorptivity of a surface are hence required.

Calorimetry [3] is an accurate technique commonly used to characterize absorptivity; however, this technique entails a complex experimental setup that is somewhat limited in terms of its application in an industrial setting. Estimation of absorptivity through inverse heat transfer analyses that involve temperature measurements poses several challenges, given the steep temperature gradients ($\sim 10^5$ °C/m) and short heating cycles ($\sim$0.2 s) that prevail in laser heating applications. Thermal inertia and contact heat transfer resistance limit the use of thermocouples [4], while infrared techniques necessitate specialized equipment that require intricate calibration. It is therefore evident that there is a need for a simple, cost-effective technique for determining the absorptivity of a surface in a rapid and reliable manner. Accordingly, this paper details a method that utilizes heat sensitive paints as the agent for temperature measurement.

2. Proposed technique

Temperature indicating paints (also available commercially in the form of crayons and pellets) have heat-sensitive inorganic pigments dispersed in them, and are formulated to melt at a certain temperature. These paints change their appearance on melting and leave an irreversible, perceptible boundary that corresponds to the melt front. On application of these paints on the surface of a sample, it is therefore possible to determine if the corresponding melting temperatures were reached or exceeded in it at that location. As per the manufacturer (Omega Engineering, Inc., USA), the paints are accurate to within 1% and have a response time on the order of 1 ms. Temperature indicating paints have been previously applied in applications referring to metal cutting [5], and gas turbine blades and rocket motors [6, 7].

The absorptivity estimation method presented in this paper entails the correspondence between the subsurface temperature profile in the workpiece measured using heat sensitive paints and that obtained from an analytical moving heat source model [8]. Six different paints that correspond to various melting temperatures in the range of 260 to 816 °C were applied in the form of thin strips parallel to each other, on the edge face of the workpiece that is perpendicular to the laser irradiated surface (Fig. 1a shows four such paint strips). During the experiment, the laser was traversed along the workpiece edge such that the beam width is parallel to the laser scanning direction. The corresponding temperature profile was determined by measuring the depth d to which melting had occurred in each paint strip (as indicated in Fig. 1b for two of the paints) using a tool makers' microscope. Three repeated measurements obtained thus were used.

The moving heat source model does not account for edge effects as it pertains to a semi-infinite solid. In order to establish a correspondence between the model and the experimental configuration above, the beam footprint was modeled by doubling the beam length and maintaining a power density consistent with experiments (Fig. 2). The edge face of the workpiece on which the temperature indicating paints were applied was thus considered as the plane of symmetry and an adiabatic surface. The moving coordinate system referred to the geometric center of the beam footprint. The model refers to quasi-steady state heat conduction in an semi-infinite solid, wherein the temperature is estimated by integrating a moving heat source solution over a rectangular region. The temperature in the workpiece is given [9] by

$$T(x,y,z) - T_{\circ} = \int_{-l}^{l} \int_{-w}^{w} \frac{Aq_{\circ}}{2\pi ks} \exp\{-\frac{V}{2\alpha}[s - (x - x')]\} dx'dy' \quad (1)$$

where A is the absorptivity, $q_{\circ}$ the heat flux, k the thermal conductivity, V the scanning speed, α the thermal diffusivity, l the beam length, $2w$ the beam width, $T_{\circ}$ the initial temperature, and s is calculated as

$$s = \sqrt{(x - x')^2 + (y - y')^2 + z^2} \quad (2)$$

The energy distribution in a high-power diode laser (HPDL) beam used in this work is Gaussian along its width and uniform along its length, and therefore $q_{\circ}$ is obtained as

$$q_{\circ} = q''_{max} \exp[-(x'/w)^2] \quad (3)$$

where q''_{max} is the maximum heat flux given by:

$$q''_{max} = \frac{Q}{2\sqrt{\pi} wl \operatorname{erf}(1)} \quad (4)$$

Q being the total laser power. The absorptivity of the surface is obtained by solving for parameter A in Eqn. (1) that minimizes the total residual between the subsurface temperature profile measured using heat sensitive paints and that obtained from the model.

3. Implementation and demonstration

Although the incorporation of lasers into metal cutting machine tools has been of interest for over a decade [10], the concept of laser integrated machine tools has gained much momentum since the emergence of the HPDL, as it is readily integrated into a machine tool [11]. HPDL radiation is readily absorbed by metallic surfaces, which obviates the need for absorption-enhancing coatings; they are capable of beam transport through optical fibers, and are relatively compact, efficient, reliable, and maintenance-free. They are further of good temporal stability, and of low capital and operating costs compared to other laser systems.

The experimental information presented in this paper therefore refers to a HPDL, although the technique is of course applicable to not just different lasers but other heat sources as well. The laser used was a 2 kW continuous wave HPDL with a rectangular beam footprint of size 4.0∗0.9 mm^2, which operated at wavelengths of 810/940 nm and a working distance of 85 mm. Experiments were conducted on annealed (∼210 HV) face-milled steel (AISI 4140) prismatic workpieces (22∗10∗200 mm^3) of roughness 3 μm Rz.

For continuous heating due to a heat source moving with a constant velocity, application of the quasi-steady state analytical model for temperature estimation is appropriate [12] provided a time $t_{qs} = (20\alpha/V^2)$ has elapsed after the initiation of heating, where the thermal diffusivity α and the scanning speed V are expressed in cm^2/s and cm/s, respectively. The analytical model disregards the temperature dependence of the thermal properties of the workpiece material and the heat losses from the workpiece, in addition to assuming that the workpiece is physically semi-infinite ignoring possible internal heat buildup. To assess the extent of the temperature variance that could arise from the effects above, a transient finite element (FE) model with three dimensional elements was formulated. Temperature-dependent thermal conductivity and specific heat data were obtained from [13] for AISI 4140 steel.

Fig. 3 shows a comparison of temperature profiles obtained from the analytical and FE models. While the temperatures predicted by the FE models deviate from the analytical model in the vicinity of the surface, the discrepancy can be seen to be negligible for temperatures below the surface, say at and below a depth of 0.5 mm. Computations further showed negligible deviation in terms of radiation and convection heat transfer, and finite workpiece volume. Given that the analytical model is adequate for predicting the subsurface temperature profile, and that it is indeed the subsurface temperatures that are relevant in the estimation of absorptivity using heat sensitive paints, it is expedient to apply the analytical model on account of it being computationally less intensive. In the event of surface melting, the related latent heat effects can also be neglected, as they have been shown [14, 15] to have an insignificant effect on the subsurface temperature.

Fig. 4 shows temperatures measured using heat sensitive paints, and the best fit model for a laser power of 400 W and a scanning speed of 0.6 m/min. The adequacy of the analytical solution is well corroborated by the excellent qualitative conformance between the computed and measured temperature profiles. The best fit in this instance corresponds to an absorptivity of 66%, which is within the range typical of HPDL application for steel [3], validating the applicability of the proposed technique.

4. Conclusions

The application of heat sensitive paints in estimating the absorptivity of a surface has been demonstrated. The technique is simple, entails no significant workpiece preparation, and is applicable to workpieces with complex geometry. The use of such paints in conjunction with an analytical heat transfer model is a simple, cost-effective and practically relevant technique for the estimation of the absorptivity of a surface in an industrial setting. This is valuable in terms of the application of models for the manufacturing process planning of high-value components. Considering that several factors related to the paint, curve fitting and model parameters contribute to the measurement uncertainty in this technique, extensive further work is required to quantify this through comparison with the established calorimetric technique.

Acknowledgments

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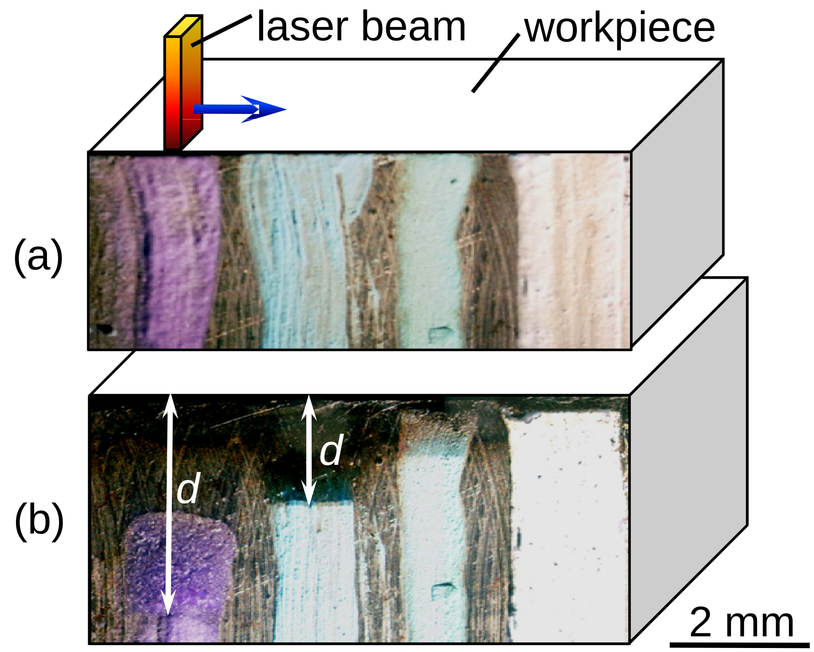

Figure 1. Temperature indicating paint strips:
(a) before, and (b) after laser irradiation.

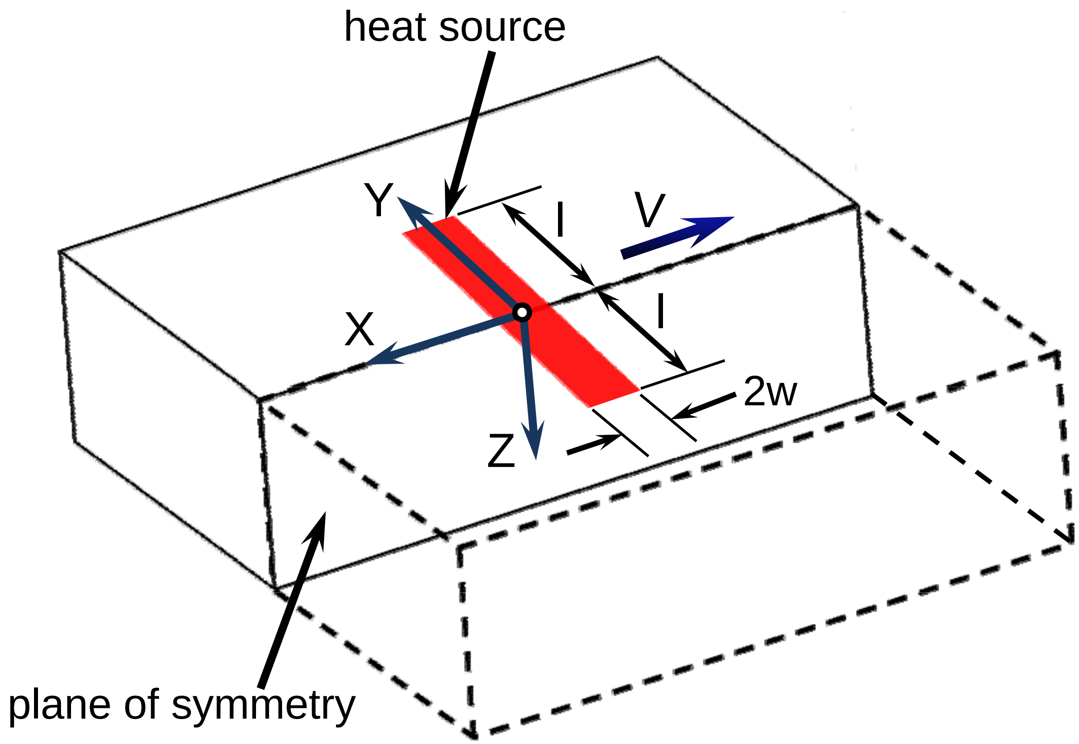

Figure 2. Model formulation for determination of absorptivity.

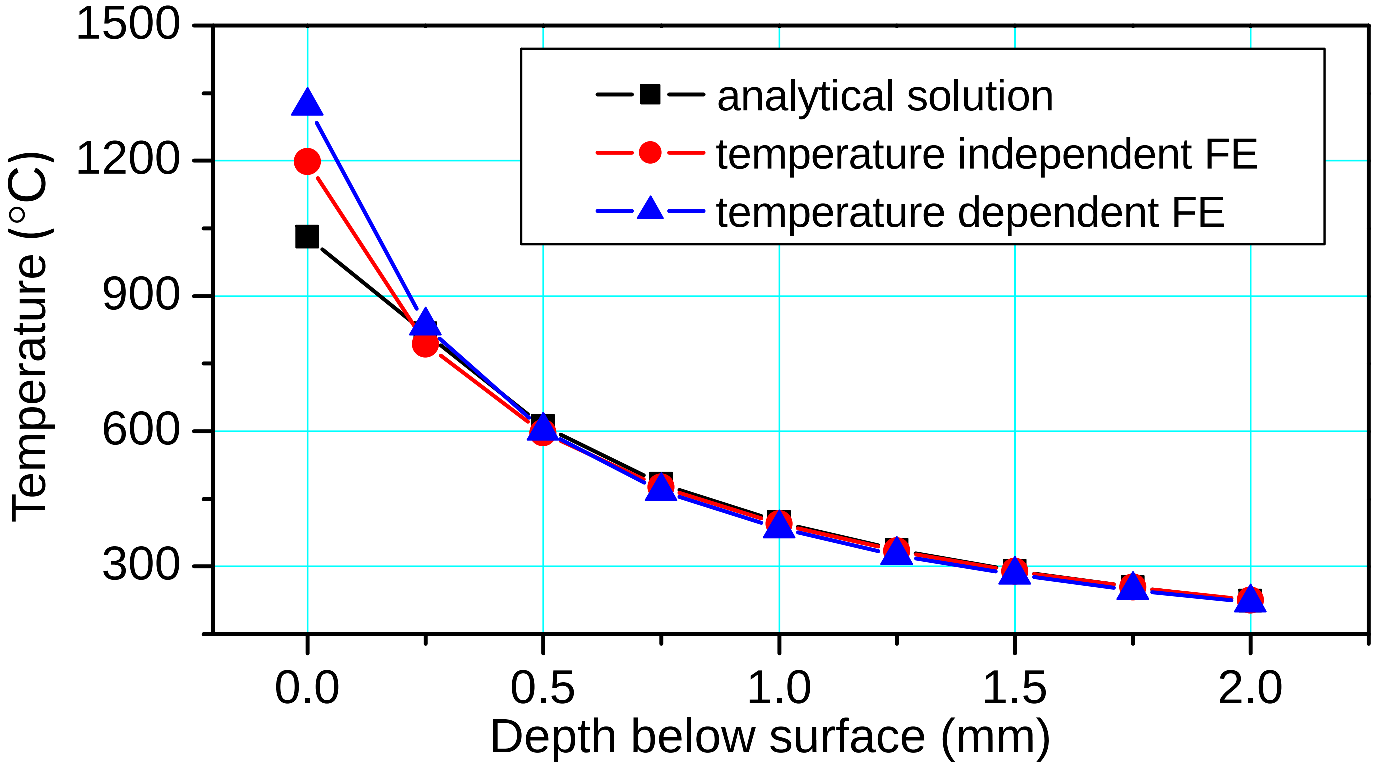

Figure 3. Comparison of temperature profiles predicted by analytical and finite element (FE) models (500 W absorbed laser power, 1 m/min scanning speed).

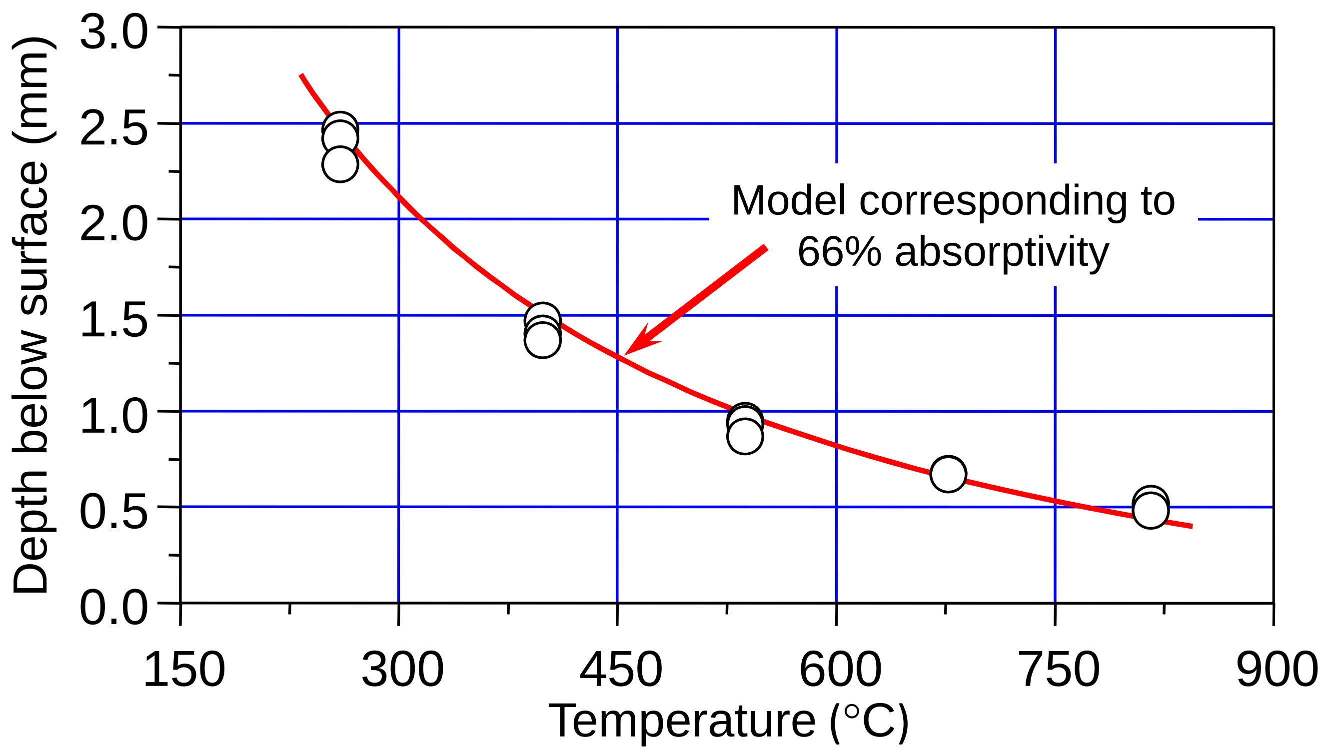

Figure 4. A comparison of typical measured (data points) and estimated temperature profile.